Fire History from the Coast Redwood Forests of Bolinas Ridge and Kent Lake Basin in the Marin County Municipal Watershed, California

by

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Wildland Resource Management

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Executive Summary

Fire scars were examined on 42 sample sections removed from redwood stumps throughout Bolinas Ridge and the Kent Lake drainage. Fire dates between 1399 and 1945 were analyzed for temporal and spatial trends in fire occurrence by compiling dates in groups of increasing sample sizes (composite groups). Larger sample sizes generally produce lower estimates of mean fire intervals because not all fires burn the entire area or are recorded on all samples.

All analyses strongly suggested that mean composite fire intervals increased since the mid-1800's; between approximately 1600 and 1850 mean composite fire intervals ranged from <2 years per 2000 hectares and 7.5 years per 5-10 hectares to a present 45+ year interval since the last fire in 1945. In addition to fires becoming more frequent (e.g. shorter fire intervals) recent fires appear to be more widespread than most fires evidenced from scars on the redwood stumps. These spatial and temporal trends are interpreted as the result of changing land uses and uses of fire by humans; frequent burning by Native Americans prior to Spanish settlement in the early 1800's maintained limited accumulations of understory and surface fuels which were probably discontinuous in many places.

Large and essentially uncontrollable crown fires similar to the events of 1945, 1923, 1904, and 1890 which have become the norm during the present era of fire exclusion are believed to have been prevented by frequent understory burning. The extreme nature of wildfires in the past 100 years, along with logging, has substantially altered the forest structure, species composition, and fuel hazard of these mixed redwood forests; these changes enhance the probability for continued wildfires of like characteristics.

Addendum: discussion of terms used in report on redwood fire history.

History vs. Prehistory

The terms historical and prehistorical were used somewhat loosely in the report because of the arbitrary distinction between historic events and those occurring prior to 'history'. Prehistoric events can be defined as those which precede written human history or modern human witness. Historic events would then be those which occurred in the more recent past. Using this scheme, fire scars evidenced on redwood samples would fall into both categories. However, all the fire dates derived from redwood stump samples could be characterized as 'historic' by persons who would consider Native Americans qualified witnesses (and perpetrators) of fire events. Other definitions may preclude any individual fire event which was not historically documented or witnessed from being classified as historical even though that event occurred within a recent time period typically referred to as historical. Distinguishing between historical and prehistorical fire occurrences is, therefore, not critical to interpreting the results of this study.

Settlement vs. Presettlement

These terms were also used rather loosely in the fire history report to distinguish only general differences in diffusely defined periods of dominant land uses. The distinction between settlement periods and pre-settlement periods or post-settlement periods is largely dependent on what condition of the territory is sufficient or necessary for such classifications. Most definitions of 'settlement' refer to European settlement, and a specific date is used in reference to an 'historic' event such as landing of a ship, or crossing a pass etc. Even if a precise year were demarcated as the boundary of 'settlement' and 'pre-settlement' periods, the decision would be arbitrary. Little is known about how even landmark calendar dates, pertinent within nearby settlements, affected use of lands (including fire) directly considered in this study.

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INTRODUCTION

Wildland vegetation throughout California has, and continues to be, profoundly influenced by fire. The nature of the fire regime (e.g. fire characteristics and effects) in many areas however, has been substantially altered since the arrival of European peoples in the late 18th century. Wildland fire regimes were changed indirectly through the displacement of aboriginals and directly through different land uses and attitudes toward fire.

Specific changes in fire regime parameters are difficult to document. Detailed written, oral, or photographic records are essentially absent from before the early 20th century. Field collections of fire artifacts, including tree age structures, fire scars on trees, and

charcoal deposits in sediments, therefore provide the principal evidence of prehistorical fire events. Fire frequency data from the low severity fire regimes that are believed to typify the redwood forest region prior to settlement are best evidenced by fire scar analysis; these data can reveal fire occurrences for hundreds of years before present. Fire events which destroy much of an existing forest stand can be dated with tree age-class analysis. Charcoal deposits in lakes or bogs can record major or long-term fluctuations in fire occurrence from thousands of years before present, irrespective of the nature of the fire regime.

The utility of fire scars to dating of fire events has been recognized since the early 1900's (McBride 1983). Almost any woody plant which survives a fire can contain a fire scar. Fire scars are recognized by the normal pattern of healing after fire induced wounds to woody tissues. Wounds are formed when lethal heating of living tissues prevents further cambial division along a localized portion of the circumference. Callus healing growth occurs as cells of tissues remaining alive on the periphery of the wound begin dividing radially as well as tangentially over the surface of the wounded area. Enlarged callus is formed as annual radial and tangential increments of woody tissues are developed in succeeding post-fire years.

When viewed in cross-section, fire scars appear as interruptions of the normal concentric tree-ring pattern.

The visible feature of a tree ring results from the annual fluctuation in secondary or radial growth rates of xylem during the growing season in temperate regions; rapid early season (spring) xylem cells are thin walled, somewhat larger in diameter, and appear lighter in color, than darker cells produced more slowly during the later part of the growing season. A fire can be dated to a given year by counting the rings between fire scars and tree-rings corresponding with a calendar date. Fires occurring early in the growing season can sometimes be differentiated from later season fires if xylem formation within a scarred area is visibly interrupted prior to completion of the annual increment during the year of the fire. A tree may accumulate many scars over time because younger callus tissues have thinner bark and less protection from lethal heating during subsequent fires. A fire scar record on a given tree, however, is often incomplete. Some fires do not scar a tree, and fires may destroy fire scars produced by earlier fires.

Fire history studies have been conducted throughout California's coastal region using fire scar evidence recorded on the coast redwood. Redwood often provides the only evidence useful for long-term fire history work in these localities because 1. the renowned rot resistance of the heartwood permits survival of fire scar records for many centuries, and 2. its great longevity allows trees to witness many fires in a life time. Other tree species may

also contain useful fire scar records from the relatively recent past, including Douglas-fir, madrone, tanoak, California nutmeg, and bishop pine.

Fire history evidence obtained throughout the redwood region unambiguously reveals a pervasive influence of fire although specific estimates of fire frequency greatly depend on the methods chosen for analysis. South of Marin County, Greenlee (1983) detailed a 56 year mean fire interval from two stumps at Big Basin State Park. Jacobs et al. (1985) reported mean fire intervals of 20 to 30 years occurring prior to the 1850's using data averaged from individual stump samples on ridges in the Marin County Municipal Watershed. To the North and inland from Marin county, Finney and Martin (1990) found mean fire intervals consistently less than 10 years from the pre-settlement period at Annadel State Park. Finney and Martin (1989) also reported mean pre-settlement composite fire intervals of 5 to 10 years within 200 hectare study areas along the coast at Salt Point State Park. Stuart (1987) found mean fire intervals of 11 to 44 years using establishment dates of redwood sprouts as indicators of fires at Humboldt Redwoods State Park. Using age-class analysis, Veirs (1981) estimated fires, which caused a substantial thinning of the redwood/Douglas-fir forest, occurred every 50 to 150 years on drier sites and upwards of 500 years on moist coastal sites; fire scar analysis suggests fires of lesser severity occurred more often. Brown (1989) found mean fire intervals

of approximately 8 years at Prairie Creek Redwoods State Park using fire scar analysis. A mean fire interval of approximately 12 years between 1849 and 1930 was derived from a redwood stump at the Northern California Coast Range Preserve (Elefant and Wakimoto 1981). From the same area Rice (1981) reported 12 year mean fire intervals from tanoak stumps corresponding to the period between 1829 and 1950.

The objective of this study was to document historical fire occurrences within Marin Municipal Watershed District lands using field evidence; written records of fires exist only from the late 1800's.

METHODS

An initial reconnaissance of the study area was conducted in June 1989 on foot and by automobile in search of vegetation types containing suitable fire history information. Redwood was the only species found which contained a fire scar record pre-dating settlement. Bolinas ridge and adjacent Kent Lake Basin was chosen as the primary study area because it was accessible for motorized transportation of the large and heavy redwood samples, and it supports extensive redwood forests along the ridge and east facing slope. A single contiguous area was desired so that multiple samples could be obtained from a well defined area. Redwood stands outside this area were also examined in order to locate fire scar samples representative of other portions of the watershed. Further reconnaissance of the

Bolinas Ridge area was accomplished in conjunction with sampling efforts.

Sampling was restricted within the chosen study area by the availability of fire scar evidence. Sampling was most productive where stumps remained from redwood trees cut after the 1940's; stumps were too rotten or damaged by wildfires to yield useable fire history information where logging occurred earlier. Wedge samples were removed from some live trees in areas where stumps were absent or otherwise rendered unusable. Wedge evidence is often inferior, however, to complete cross-sections obtained from intact stumps on which fire scars can be examined before cutting.

The pervasive influences of fire throughout the redwood forest type makes time-efficiency and information potential the chief criteria for choosing fire scar samples. Almost every redwood stump and tree has fire scar information. The best preserved samples have consistently been recovered from 'live' redwood stumps. The xylem and phloem around much of the circumference of these stumps remains active; very narrow faint growth rings continue to be produced after logging because photosynthates are transported to the stump from adjoining redwood sprouts which either originate after logging or remained from before harvest. Based on experience, samples containing the best preserved and most complete fire scar sequences were found at the apex of fire scars where the ceiling of the cavity is not hollowed

(Figure 1). On most fire scar cavities this portion of the scar is the most narrow and allows more complete healing and preservation of each scar than on lower regions of the tree stem. Arguably, some fires may not scar the tree at that elevated position (sometimes 1 or more meters above the ground), although realistically all scar samples are incomplete either because fires do not scar the tree or because evidence is destroyed by later fires. Not all samples were obtained from stumps like these or from this portion of the fire scar cavity.

Stumps selected for sampling were excavated with a chainsaw to reveal multiple cross-sections of the available fire scar sequences. As many as three sample slices were labeled with aluminum tags and removed from a stump when the exposed fire scar sequences could or were not contained on any single cross-section. Similar procedures were employed for removing wedges from an occasional live tree that both displayed an open fire scar cavity and was believed to contain a superior fire scar sequence. The location of each sample was mapped. All samples were transported to the laboratory for further analysis.

The upper and lower surfaces of each sample were sanded incrementally to a smoothness of 400 grit. Fire scars and zones of rapid change in tree ring width were located on the sample. Fire scars were identified by the characteristic disruption of the pattern of radial growth rings and accompanying interior pockets of sapwood or discolored

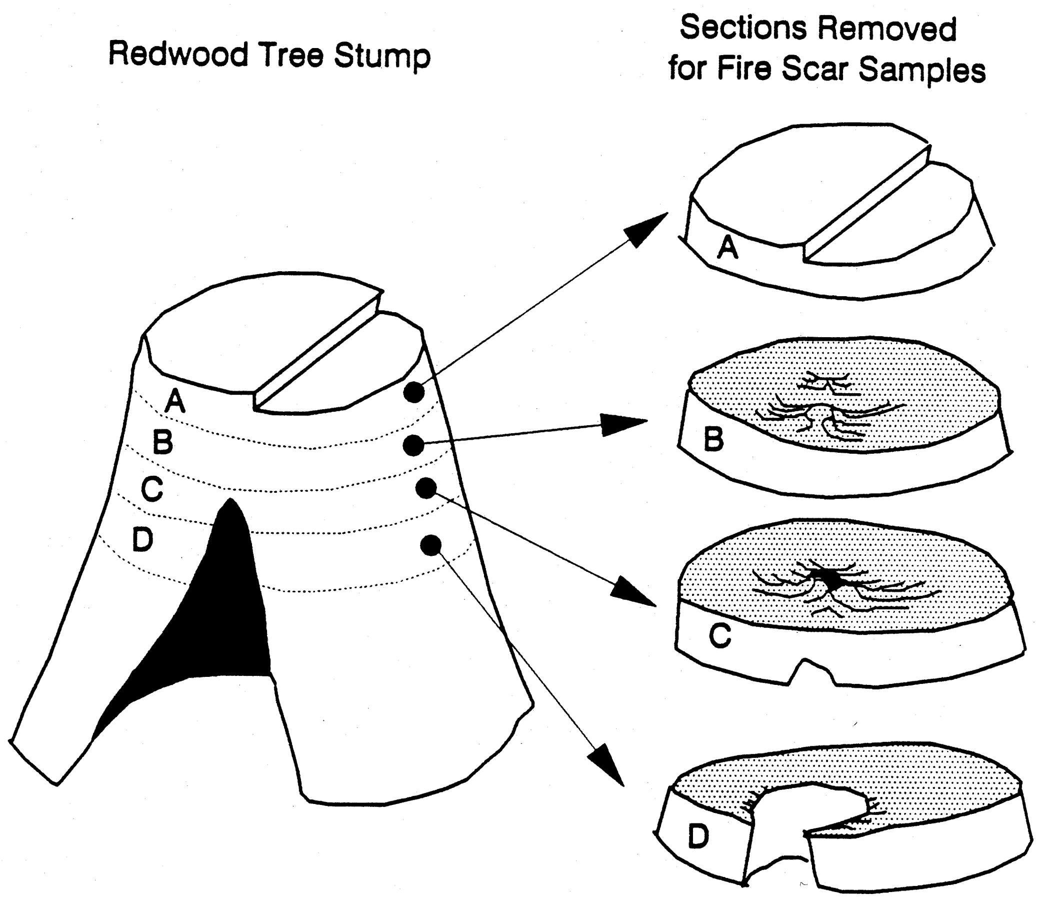

Figure 1. The most complete fire scar sequences were obtained from stumps where open fire scar cavities remained intact beneath the cut surface. Sections corresponding to "B" and "C" generally had the most fire scars. Fewer fire scars were found on lower sections because the cavities had been burned out.

heartwood caused by incipient rot. Lighter colored sapwood pockets within the margins of old fire scars are often surrounded by reddish heartwood. Locations of dramatic changes in tree ring width, which can be related to fire events, were also identified on the samples. Restrictions in increment can be caused by recovery from defoliation of the tree, and widening growth rings may reflect release following fire-caused mortality of neighboring trees in the surrounding forest.

Prescribed fire research in progress at U.C. Berkeley has shown that the coast redwood is very resilient to complete and repeated fire-caused crown scorch and defoliation. Tremendous reduction or elimination of radial increment along the lower portion of the stem during the immediate post-fire years is probably a result of changed priorities within the tree toward recovering foliage lost from the fire. Similar responses have been recorded in post-fire growth of other species (i.e. Wade and Johansen 1986). This elasticity of tree ring width complicates the process of establishing accurate dates of redwood tree rings.

Tree ring anomalies in the coast redwood were reported first by Fritz and Averill (1924) and later by Fritz (1940) and Schulmann (1940). Ring counts and cross-dating for establishing tree ages and dating events (such as fire scars) were more unreliable than on other tree species because of abrupt narrowing and disappearance of sometimes

20 or 30 rings at a time along a given radius of certain redwood cross-sections (termed "wedging-out"). Cross-dating of redwood tree rings (Schulmann 1940, Lamarche and Wallace 1972) was made more difficult because of the 'complacency' of redwood radial growth relative to somewhat constant coastal climatic conditions and ring width variation related to the above mentioned fire effects. Nevertheless, short cross-dated tree ring sequences (about 250 years) have been produced (Shulmann 1940, LaMarche and Wallace 1972, Swetnam 1987) from certain samples. Criteria for selecting fire scar samples which include abundance of fire evidence, often conflict with those specified for dendroclimatological purposes which emphasize exclusion of non-climate (i.e. fire, competition etc.) influences on tree ring sequences that may obscure patterns of climate induced ring-width variation comparable among samples in the area. Particular sample selection and effort were necessary to producing a recent cross-dated fire history (Brown 1989).

Fire dates were determined by counting of annual rings between those rings designated as containing fire scars or which had dramatically different widths from previous rings. The magnification of a binocular dissecting microscope or handlens was used where necessary. Relative season of the fire was conservatively noted only where ring disruption clearly occurred prior to termination of latewood formation. Rings were counted along multiple radii to avoid overlooking very narrow or discontinuous rings prevalent along radii

showing constricted increment; individual rings can be traced to radii where wider rings increase the likelihood of more complete ring sequences. Discontinuous rings were found most often in wood produced during the first or second growing seasons after a fire. In extreme cases these rings appear only in the widened callus growth bulging over the margins of scarred portions of the circumference; callus tissues however, often display dark streaks similar to false rings which can be confused with actual latewood bands.

A fire chronology was prepared using fire dates from all samples. The substantial additional time required for enhancing the accuracy of fire dates and ring counts using cross-dating was considered impractical for ecological and managerial objectives governing this fire history study. Instead, the accuracy of fire dates was assessed and improved by comparing fire interval sequences among samples taken in the same general area. Procedures were similar to those detailed by Madany et al. (1982). Rings containing fire scars and other indicators were designated on strips of graph paper where each cell represented a single ring as blackened or outlined squares, respectively. To begin with, strips from nearby samples were grouped and positioned next to each other in order to align the almost ubiquitous indicators of the two most recent fires which were known to have occurred in 1945 and 1923 (from fire records). Dates of earlier fire indicators were then corroborated by iteratively comparing the length and sequential pattern of

fire intervals from progressively older time periods, rechecking ring counts on the wood sample between those fire dates for which a discrepancy was suggested, and again comparing fire interval sequences on strips containing updated ring counts.

Samples on which discontinuous or faint rings were consistently discovered during subsequent examinations were given less credibility than others when establishing the master fire chronology. On several less-reliable samples where recounting failed to reveal missing rings suspected in a given fire interval, adjustments of up to 3 additional years were tentatively inserted into that interval as an attempt to improve correlation between fire dates earlier in that sequence and fire dates recorded by other samples in the comparison. An adjusted fire interval sequence was accepted into the final chronology only when the adjustment resulted in successful matching between older fire dates. Fire interval sequences from samples for which the adjustment procedure failed were included in the chronology in their original form.

A variety of techniques were used to analyze the spatial and temporal variation in the fire history data because interpretations are so strongly influenced by the choice of methods. Data from individual samples were analyzed independently as well as by aggregating the samples into 8 composite groups (Dieterich 1980) based on geographic separation of sample clusters. Composite data must be

interpreted along with the size of the sample area whereas data from individual samples is assumed to represent a one-dimensional point estimate without 2-dimensional area.

Temporal aspects of the data were investigated by computing mean fire intervals for individual samples and composite groups for centuries and half centuries, respectively. Century length summaries are more reasonable for fewer data obtained from individual samples. The median fire interval was also estimated because fire interval distributions from redwood are often non-normal (Jacobs et al. 1980, Finney and Martin 1989); medians were estimated by converting means of fire interval data transformed by natural logarithm (commonly used to normalize skewed distributions) back to natural units.

Spatial dimensions of fire activity were assessed by calculating mean and variance around the mean for fire intervals for individual samples, and using fire dates from increasing numbers of samples. The percent of fires common to composite groups of 2, 4, and 8 samples was calculated and plotted against chronological time. Distributions of fire intervals, which illustrate the nature of variability in fire intervals were also computed over the range of area or distance by century. Finally, fire dates were mapped by sample location in order to provide the most comprehensive, though qualitative, illustration of temporal and geographic variation in fire occurrence.

years between the last half of the 18th century and the first half of the 20th century. Similarly, MCFIs for individual composite groups (5-10 ha) increased from 7.5 to 18.1 years between the same periods. Mean fire intervals from individual samples do not reveal this trend because of the much higher variance associated with individual samples and the larger ranges of the fire interval data. Minimum mean fire intervals from individual samples, however, do confirm the trend toward increasing fire intervals during the 19th century because only the most complete fire scar sequences for a given century are represented. Mean fire intervals from individual samples for the 16th, 17th, and 18th centuries ranged from 6.2 to 100 years, 6.5 to 93.0 years, and 8.8 to 80 years, respectively (Table 1). Mean fire intervals from individual samples for the 19th century varied between 11.6 and 99 years and from 20.5 to 45 years for the period between 1900 and 1945.

Spatial Variation in Fire Occurrence

Mean fire intervals from composite groups across the study area were similar for a given time period and suggested similar temporal trends (Appendix 1). Larger variance associated with higher half-century mean composite fire intervals, possibly related to different sample numbers and qualities within composite groups, precludes a distinction between fire intervals in valley sites near Kent Lake and sites on Bolinas Ridge. MCFIs decrease predictably

Table 1. Summary statistics for composite fire intervals different sized groups of samples.

TIME PERIOD	MEAN	MEDIAN	SE (years)	MAX	MIN
	INDIVIDUAL GROUPS OF SAMPLES(5-10 HA)				
1945-1990	45.0	45.0		45.0	45.0
1900-1945	18.1	17.8	3.7	22.0	13.7
1850-1900	14.0	11.9	9.4	33.0	6.4
1800-1850	10.6	9.4	5.3	18.2	3.8
1750-1800	7.5	6.5	4.0	14.3	2.7
1700-1750	8.8	7.5	5.4	17.5	3.6
1650-1700	11.2	9.0	8.4	25.3	4.8
1600-1650	10.6	10.3	2.6	13.8	6.0
1550-1600	17.5	14.2	13.7	41.0	7.5
1500-1550	18.0	14.8	14.0	34.0	8.1
1450-1500	19.7	14.2	19.4	33.4	6.0
1400-1450	48.5	48.5		48.5	48.5
	PAIRED GROUPS OF SAMPLES (20-60 ha)				
1945-1990	45.0	45.0	---	45.0	45.0
1900-1945	12.1	12.0	1.8	13.7	10.3
1850-1900	7.0	6.7	2.3	12.8	5.1
1800-1850	4.4	4.3	1.2	7.1	3.5
1750-1800	3.8	3.5	1.8	7.4	2.2
1700-1750	4.6	4.2	2.3	9.3	2.7
1650-1700	6.4	5.2	5.6	20.7	3.2
1600-1650	7.0	6.7	2.3	10.5	3.7
1550-1600	8.7	8.1	4.0	16.0	5.3
1500-1550	18.7	14.1	14.0	32.5	5.2
1450-1500	16.6	12.7	15.4	34.3	7.2
1400-1450	30.0	30.0	30.0	30.0	30.0

Table 1. continued.

TIME PERIOD	MEAN	MEDIAN	SE (years)	MAX	MIN	NUMBER OF FIRES
	FOURSOME OF SAMPLE GROUPS(100-500 Ha)					
1945-1990	45.0	45.0		45.0	45.0	
1900-1945	14.6	2.7	2.6	20.5	13.7	
1850-1900	4.5	1.5	0.8	5.7	3.4	
1800-1850	3.2	1.1	0.7	4.6	2.5	
1750-1800	1.9	0.6	0.4	2.8	1.5	
1700-1750	2.3	0.8	0.3	2.8	2.0	
1650-1700	2.4	0.9	0.4	3.2	2.0	
1600-1650	3.5	1.2	0.5	4.5	2.8	
1550-1600	4.3	1.5	0.6	5.3	3.7	
1500-1550	17.6	2.6	12.6	29.0	4.6	
1450-1500	9.5	2.2	2.8	12.8	7.2	
1400-1450	30.0	3.4	0.0	30.0	30.0	
	ALL SAMPLES COMBINED (2000 HECTARE)					
1945-1990	45.0			45	45	0
1900-1945	13.7	9.1	10.4	22	2	3
1850-1900	3.0	2.0	3.4	14	1	18
1800-1850	1.8	1.6	1.1	6	1	28
1750-1800	1.3	1.2	0.7	4	1	37
1700-1750	1.5	1.4	0.8	4	1	33
1650-1700	1.5	1.3	0.9	5	1	34
1600-1650	1.7	1.4	1.0	5	1	60
1550-1600	3.0	2.5	2.1	9	1	16
1500-1550	4.2	3.4	2.9	11	1	12
1450-1500	7.2	5.9	4.8	16	2	6
1400-1450	30.0	26.5	19.8	44	16	2

as composites are calculated from larger numbers of samples from larger areas except during the 20th century (Figure 3). This suggests that the fewer recent fires were more widespread than typically smaller or more patchy fires occurring during preceding periods. The trend is further illustrated as a sharp 20th century increase in the coincidence of fires among all sizes of sample groups and land areas during later time periods (Figure 4). Fire interval distributions (Figure 5) reveal decreasing range and increasing concentration of shorter fire intervals as data are derived from larger sample sizes and areas.

The approximately 30 fire scars (Figure 6) dating from before about 1880 found on a single stump sample removed from Fish Gulch to the east of the Bolinas Ridge study site suggest that the fire intervals from the Bolinas Ridge and Kent Lake area were not unusual throughout the forested portions of the watershed. Fire intervals could not be determined accurately on this sample because the tree ring sequences were very constricted and discontinuous around the sample; rings were often visible only in the callus growth.

DISCUSSION

Sequences of fire scars and intervals obtained from individual redwood samples in this and other studies (i.e. Finney and Martin 1989) are believed to be very incomplete records of the actual levels of fire occurrence. Reasons include a lack of correspondence between adjacent samples,

Figure 3. Mean composite fire intervals for groups of different sizes.

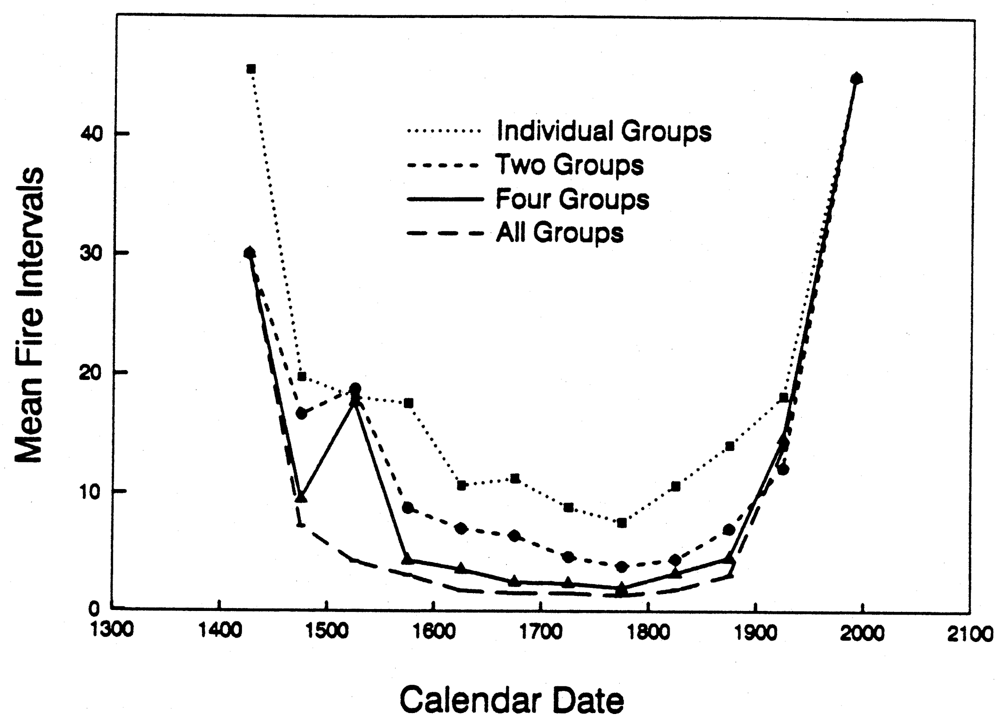

Figure 4. Frequency of fire dates common to composite groups of different sizes.

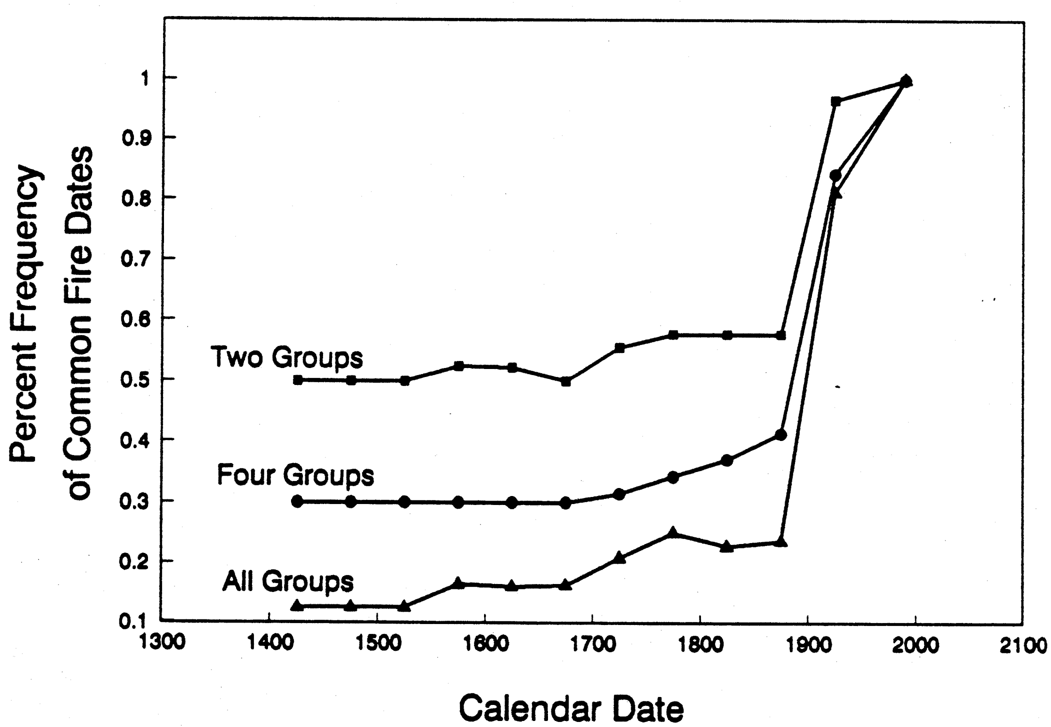

Figure 6.

(PHOTO)

Not Included (yet)

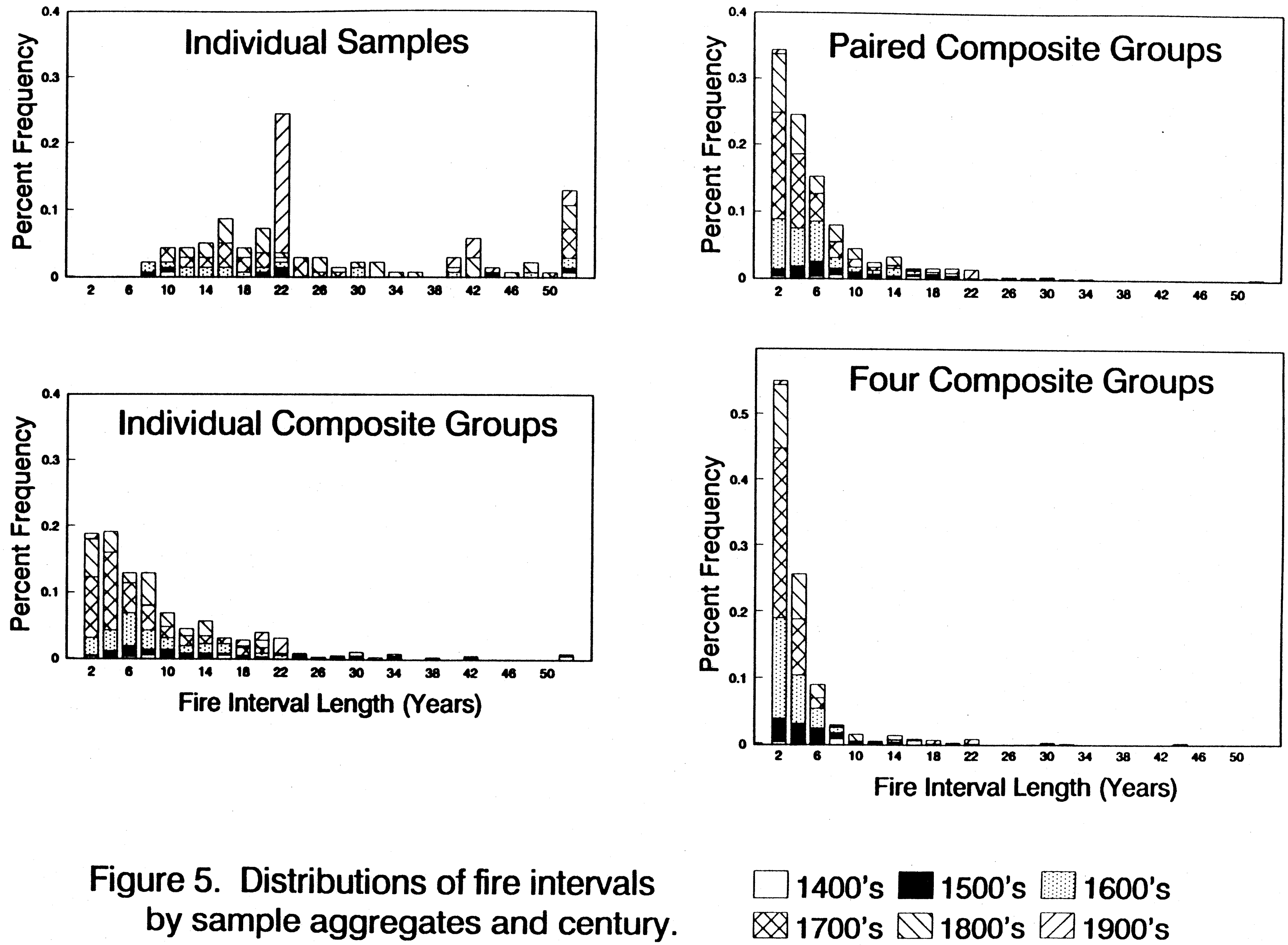

Figure 5. Distributions of fire intervals by sample aggregates and century.

fire caused ring-width changes without associated fire scars (Brown 1989), and burned-out or decayed edges of fire scar cavities. In addition, mapping fire dates according to sample location (Appendix 2) clearly illustrated the geographical positioning of scar dates and the inconsistent recording and (or) survival of fire scars within the probable perimeter of a given fire. Interpretations of composite fire data however, must consider the size of the fires relative to the study area. Larger areas and sample sizes used for composites will generate shorter mean composite fire intervals if fire sizes were small relative to the size of the study area. Thus, decreases in MCFIs will result if evidence on individual samples is incomplete or if fires can burn only part of a study unit.

Interpretations of fire history data can be complicated by methods of data analysis as well as artifacts or trends apparent in the data that result from other than actual trends in fire activity (as with the above mentioned dependence of MCFIs on relative fire sizes). For example, imprecisions in assigning calendar dates to fire scars can lead to shortening of composite fire intervals because a given fire may be erroneously dated for different samples to different years. This problem was reduced by checking fire intervals among adjacent samples and recounting suspect intervals. Mean fire intervals calculated from similarly corrected sequences were nearly identical to those from crossdated master fire chronologies (Madany et. al. 1982).

Although crossdating permits the most accurate determination of individual fire dates, summary descriptions (means, medians, variance) of fire regime parameters such as fire intervals are of more practical and ecological importance.

The fire scar data on seasonality of historical fires is inconclusive, although early season fires were found throughout the recorded history. Analysis of seasonality from fire scar data may be biased against recording of early season fires because higher fuel moistures in spring may not permit sufficient fuel consumption during a fire to scar trees.

Natural deterioration of fire scars over time tends to result in artifactual increases in mean fire intervals calculated using older data because fewer records remain from more ancient fires. This trend is depicted in Figure 3 of the fire history data from the Bolinas Ridge and Kent Lake area as an elevated mean fire interval prior to the 1600's as well by the overall positive slope of fire coincidence lines in Figure 4. Thus, these fire scar data for periods prior to approximately 1600 should be interpreted with caution although data from more recent periods are believed reliable. Much of the evidence predating the 1600's was likely to have been destroyed with 19th early logging of the largest and oldest trees and subsequent deterioration of stumps.

Data suggest that mean fire intervals have increased dramatically since around 1800. Estimates of presettlement

(1600-1800) mean fire intervals vary between 4 and 10 years/ 5 hectare areas encompassing individual composites to consistently less than 2 years/1000 hectares for all samples within the entire study area. Reduction of fire intervals with sample numbers and increasing area is typical for many fire history data (Arno and Peterson 1983) from areas where fire sizes were smaller than study areas. By comparison, fire intervals have lengthened since 1800 to the present fire free interval of 45 years after the large fire of 1945.

Fires that burned in the study area since 1900 appear to have been more extensive than earlier fire events, although boundaries of older fires in this area are impossible to accurately reconstruct. Reconstruction of fire boundaries is possible and practical from some data from some fire regimes (e.g. Heinselmann 1972, Tande 1979, Hemstrom and Franklin 1979, Agee et al. 1990) in areas containing effective natural fuel breaks or impediments to fire spread (i.e. natural lakes, rock slides etc.). Barriers are generally absent in the continuous fuel and vegetation covering the Bolinas Ridge/Kent Lake area, although fire spread could be limited by moist ridge-top fuels related to prevalent summer fog-drip on Bolinas Ridge. This was not pursued, however, because Bolinas Ridge also represented a study area boundary.

Maps of fire scar dates by sample location (Appendix 2) as well as written records of fires, fire sizes, and fire boundaries, indicate that the fire of 1945 and 1923 occurred

at almost all sample locations within the study area. Evidence of a fire in 1904 was also very widespread. The fire in 1890 was recorded on most samples taken from Bolinas Ridge and was documented by newspapers as burning over this entire area. Earlier in the 19th century, fires appear to have been more numerous and fire evidence more localized on the fire occurrence maps although there were some fire dates recorded more extensively (i.e. 1837, 1824, 1811). During the 17th and 18th centuries from which data are considered reliable, fires apparently occurred almost every year at some location within the study area.

Interpretations of the many closely space fire dates from before the mid-1800's are dependent on assumptions of the fire regime responsible for those records (i.e. human vs. non-human control). Fire history methods and interpretations of data have been mainly developed for, and applied to, situations typified by a regime of unintentional burning (Lewis 1980). Lewis (1980 p. 115) states..

> "...hunters and gatherers employ patterns of burning which are significantly different from natural patterns of ignition and, with both manmade and natural fire regimes occurring throughout a given region and range of micro-habitats, <u>information derived from fire scars may provide little real insight into the chronology and frequency of fires</u> (emphasis added).

> ...Paradoxically, it is the very ways in which prescribed burning has been used that accounts for its environmental importance <u>and</u> the paucity of fire scar evidence."

Explanations of the short interval fire scar evidence in terms of strictly non-human sources of ignition and weather dependent fire spread would require parallel evidence of lightning activity or climate conditions dramatically different from today. No climatic data are known to suggest improved wildfire conditions during pre-settlement periods. However, ignitions and fire spread would be largely independent of annual weather variation if Indians were responsible because conducive conditions for intentional burning by multiple ignition would likely occur during certain days or weeks every year.

Indians certainly played a very important, if not dominant, role in determining the pre-settlement fire regime (and thus the fire scar record) in coastal California vegetation. A discussion of the extensive burning by aboriginal peoples throughout the coast redwood region has been presented earlier by Lewis (1973). Indians are known to have burned prairies among redwood forests in Humboldt County as late as the 1850's (Veirs 1987). Sugnet (1985) summarized existing written records of Indian burning at Point Reyes adjacent to the Marin County Municipal Watershed. These records along with the arguments of Lewis

(1973) suggest that Indian uses of fire were pervasive. Sugnet (1985) cites an account of Sir Francis Drake's departure from Point Reyes in 1579 from Fletcher (1628) when burning was witnessed.

> "The 23rd of June they (Miwok Indians) took a sorrowful farewell of us, but being loath to leave us, they presently ran to the top of the hills to keep us in their sight as long as they could, making fires before and behind, and on each side of them...."

Another first-hand report of recently burned vegetation near Point Reyes was made by Archibald Menzies in 1790. In 1823 Altimira traveled through an area immediately before Indian burning in present day Sonoma County (Sugnet 1985).

Lewis (1980) notes that burn coverage across landscapes which are burned frequently by aboriginals is patchy and results in an alternating mosaic of burned areas. A given point may burn only when local fuels and nearby ignitions permit although extensive areas may be burned by separate ignitions. The fire scar evidence is perhaps more limited by the presence of fuels under regimes of intentional burning than the presence of fires as occurs in situations without such human control. Individual fire scar samples in this study revealed minimum fire intervals of 3 years and more commonly 4 and 5 years. No single sample revealed the

recent 2-year interval between fires documented as partially overlapping in 1904 and 1906 on the northern end of Bolinas Ridge. Fire intervals of 2 and 3 years on individual samples found at Annadel State Park (Finney and Martin 1990) may reflect rapid development of surface fuels such as grasses beneath forests that were more open than those over much of Bolinas Ridge. Short fire return intervals are possible in understories of closed-canopies of coast redwood forests as well. Recent prescribed fire research at U.C. Berkeley indicated that fine fuels were deposited in sufficient quantities and continuity beneath scorched redwood trees to carry a fire in autumn only 3 to 4 months after a spring burn. Even more foliage is deposited within clumps of redwood sprouts. Redwood foliage may be available shortly after many burns because redwood can repeatedly recover from crown scorch.

The contribution of lightning sources of ignition to the fire regime is unclear. Lightning is relatively uncommon along coastal areas of California (Komarek 1967, Schroeder and Buck 1970) compared to the frequency of fires evidenced there. Separation of lightning-caused fires from the combined record would be impossible even if strike frequencies and densities were known because the potential for successful ignition and fire spread were altered by the effects of intentional fires on the fuels and vegetation (Minnich 1989).

increases in fire sizes and intervals between fires. The characteristics of the latest wildfires (1890, 1904, 1923, and 1945) have been sufficiently different from the former fires as to drastically change the forest structure. The fires in 1890, 1904, 1923 and 1945 burned under extreme wildfire conditions as evidenced by general descriptions of the fires (documented from newspaper accounts by Peter Martin), number of homes destroyed, and the redwood "fire columns" and spike-top trees visible throughout the hills and slopes surrounding Lagunitas Creek. Compared to fires before settlement these fires were probably of higher fireline intensity with zones of crown-fire and torching trees. Fuel loads (and presumably fuel consumption) were likely higher at the time of recent fires because more fuel had accumulated during the longer fire intervals. Higher fuel consumption relates to larger heat release and increased mortality of above- and below-ground plant parts. Repeated fires with these characteristics in the coastal mixed evergreen forests tend to favor hardwood dominated stands (Thornburg 1982) because many hardwoods can sprout and grow rapidly whereas Douglas-fir must reproduce by seed and grows slower when young.

Vegetation and fuel changes can be broadly classified as occurring in overstory and understory strata; changes from presettlement structures and composition are greatest where recent wildfires have had the most extreme fire behavior and/or logging the greatest impact. In many areas

bordering Kent Lake and along Lagunitas Creek where crown fire or very high intensity surface fires prevailed during 1945 and/or 1923, tanoak and other hardwoods have entirely replaced Douglas-fir among both overstory and understory strata and now dominate most of the area between widely scattered redwood residuals and sprouts. Large Douglas-fir snags and stumps beneath hardwood overstories testify to the lost codominance of Douglas-fir that had been maintained under the pre-settlement fire regime. Structure and composition of forests in the remaining old-growth groves in Lagunitas Creek below Alpine Lake dam suggest that tanoak was maintained as small trees and sprouts (Tappeiner and McDonald 1984), susceptible to top-killing by the frequent pre-settlement surface fires. Overstory Douglas-fir had been large enough to withstand most of those fires. Douglas-fir may eventually invade hardwood dominated stands from surrounding seed sources and later penetrate the overstory as tanoak and madrone decline and leave gaps in the canopy (Thornburg 1982).

Other forests (along Bolinas Ridge and north part of Kent Lake around Peters Dam) that were less severely affected by the recent fires remain dominated by Douglas-fir and redwood but have dense hardwood and evergreen shrub understories. Fire regimes and changes in vegetation in areas such as chapparral and grasslands are difficult to interpret using fire history data from the redwood forests.

The probable fire behavior in many forests is now likely to be more extreme than under the presettlement regime. Although surface litter fuels beneath dense stands of strictly tanoak and madrone are less flammable than conifer litter under most weather conditions, the combination with higher understory coverage of evergreen shrubs (Vaccinium, Ceanothus etc.) contributes to potentially higher surface fire intensities under extreme conditions (Atzet and Wheeler 1982). Shrubby fuels also facilitate transition from surface fires to crown fire. Thus, frequent low intensity surface fires in primarily conifer litter before settlement have probably been replaced by less frequent fires of higher intensity which will perpetuate the hardwood domination in areas between clumps of resistant redwoods. Restoration of frequent surface fires in the most severely impacted areas would be difficult with the present stand and surface fuel conditions.

Fire history has not been the same for all redwoods. Dense thickets of small diameter redwood in areas without older residual trees probably originated from sprouts maintained in stunted form by high intensity fires typical of surrounding chapparral. Manzanita burls can be found half-buried beneath many of these redwood stands and suggest that redwoods developed to dominate former shrublands after fires were excluded. Edaphic conditions probably preclude this type of invasion or succession on most chapparral sites. Examples of early stand characteristics with redwood

sprouts emerging from chapparral are visible on south flank of Mt. Tamalpais and are likely similar to those preceding the dense redwood thickets of today.

CONCLUSIONS

The fire regime in the redwood forests of Bolinas Ridge and Lagunitas Creek has changed substantially since the early-1800's. Indian burning probably occurred somewhere in the study area almost every year although fire scar records on individual trees are incomplete because fires were patchy and partly limited by fuel availability. Forest structure and species composition has also been altered by the recent fires and logging toward increased hardwood domination. Fuel complexes in forested areas are capable of supporting extreme fire behavior relative to fires believed common before settlement. Higher understory shrub densities and loadings of dead and downed surface fuels contribute to the potential for more fires like those that have burned during the first half of the 20th century.

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Appendix 1. Summaries of mean composite fire intervals (years) and standard errors by individual composite group (designated by Roman numeral).

	I		II		III		VI	
	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE
1900-1945	22.0		13.7	10.4	13.7	10.4	13.7	10.4
1850-1900	33.0	5.7	6.8	6.6	12.3	5.3	8.2	7.0
1800-1850	13.8	6.2	3.8	3.6	16.7	8.7	7.3	4.1
1750-1800	8.3	4.0	2.7	1.8	6.5	7.3	3.5	2.8
1700-1750	6.4	5.0	3.6	1.9	10.0	7.1	4.3	2.1
1650-1700	10.0	7.9	4.8	2.4	25.3	14.0	7.3	5.3
1600-1650	13.8	12.1	6.0	4.7	10.3	5.0	12.7	6.4
1550-1600	4.1		7.5	3.8			14.8	2.4
1500-1550	11.8	12.1	8.1	2.7			34.0	
1450-1500			6.0		33.4	56.5		
1400-1450			48.5	46.0				

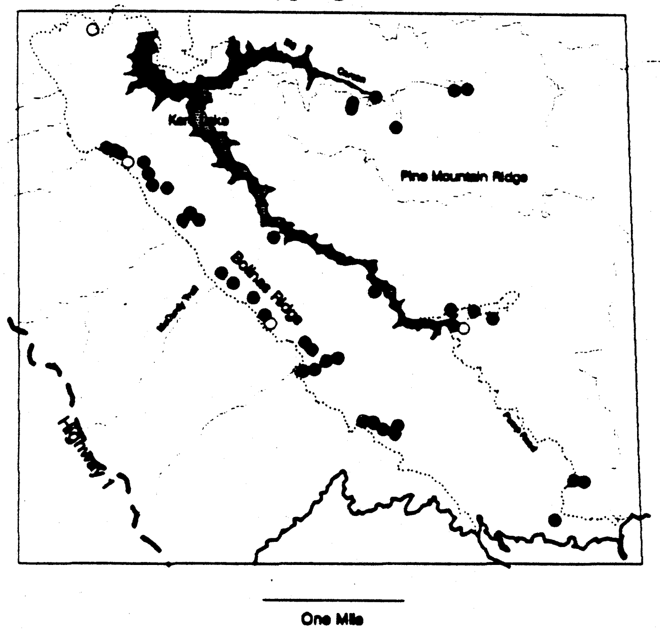
	V		VI		VII		VIII	
	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE
1900-1945	20.5	2.1	20.5	2.1	20.5	2.1	20.5	2.1
1850-1900	12.8	10.7	6.4	4.6	19.0	14.1		
1800-1850	8.4	2.4	5.2	3.2	11.8	12.9	18.2	25.7
1750-1800	14.3	4.2	4.2	2.9	9.4	7.2	10.8	7.5
1700-1750	16.3	13.1	4.5	3.5	7.8	4.8	17.5	0.7
1650-1700	4.8	2.9	5.4	4.1	20.7	9.5		
1600-1650	12.3	9.4	10.5	3.7	8.8	3.2		
1550-1600	8.0	6.0	16.0	10.6				
1500-1550								
1450-1500								
1400-1450								

Appendix 2. Maps of fire dates by sample location.

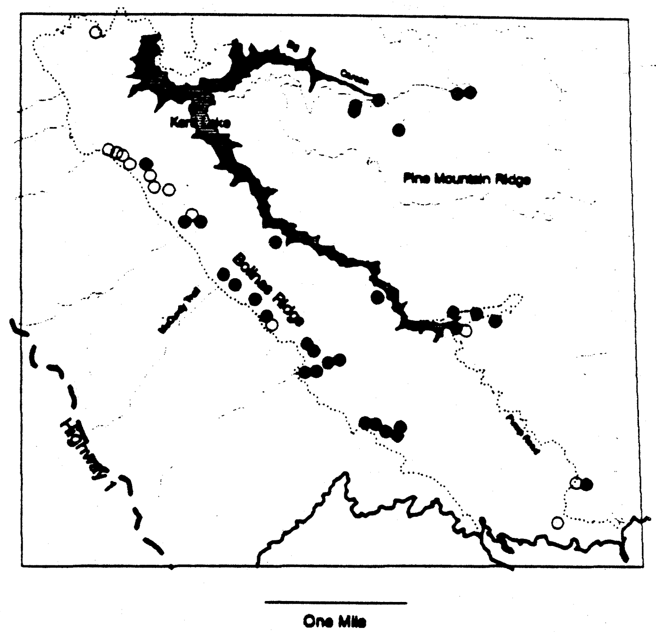
(Fires mapped between 1700 and 1945)

Marin County Municipal Watershed
Bolinas Ridge and Kent Lake

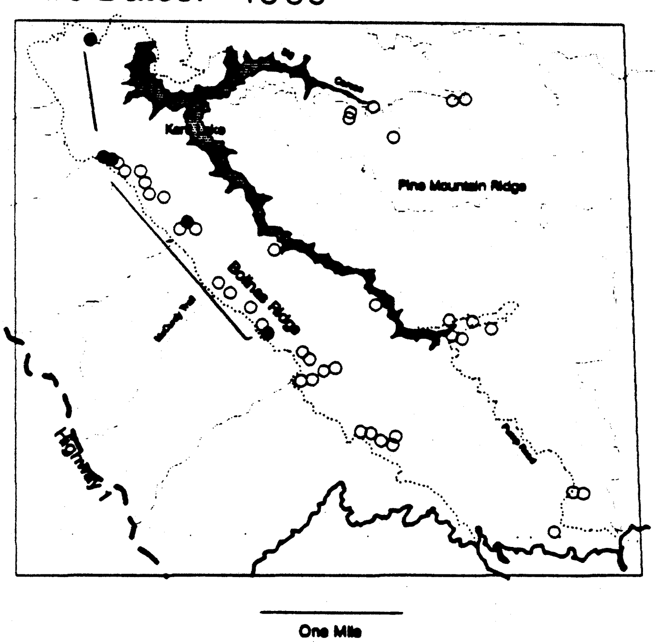
Fire Dates: 1945



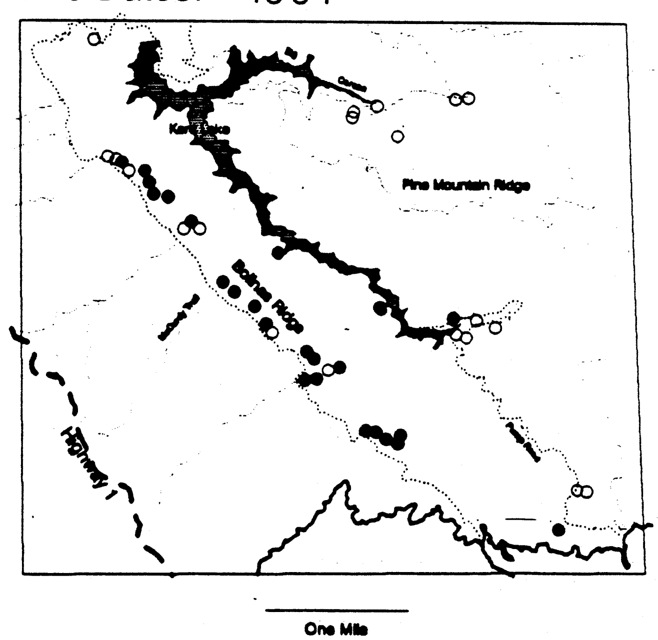
Fire Dates: 1923



Fire Dates: 1906

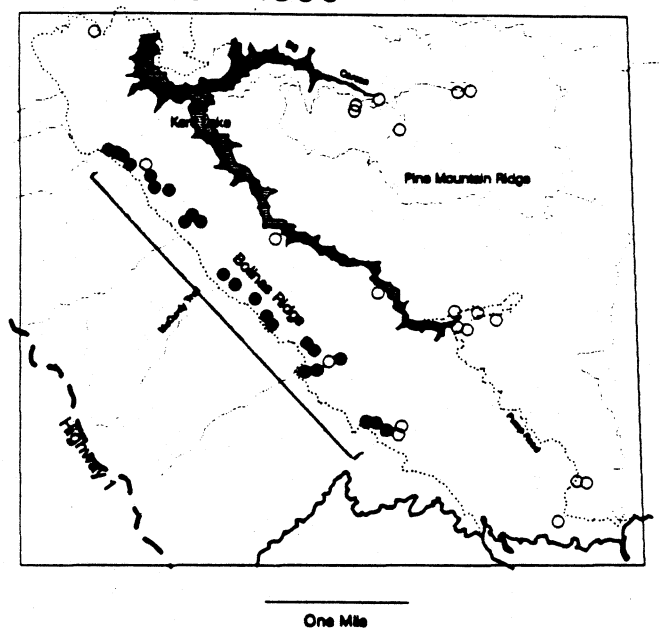


Fire Dates: 1904

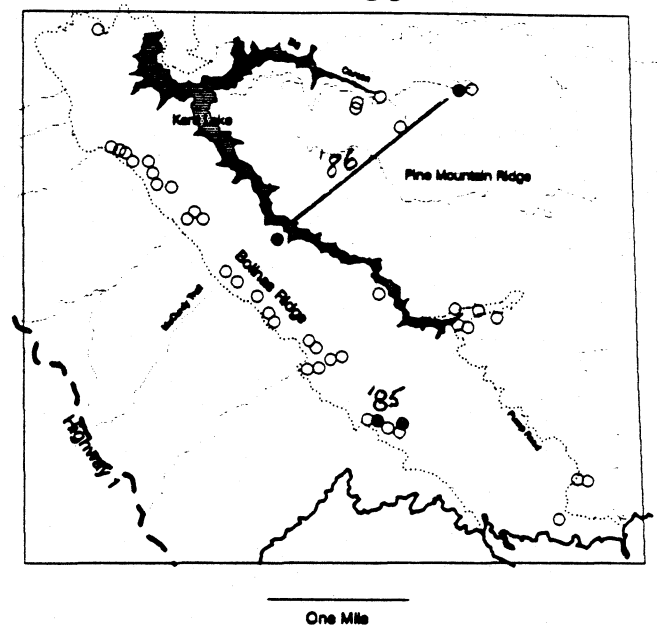


Marin County Municipal Watershed
Bolinas Ridge and Kent Lake

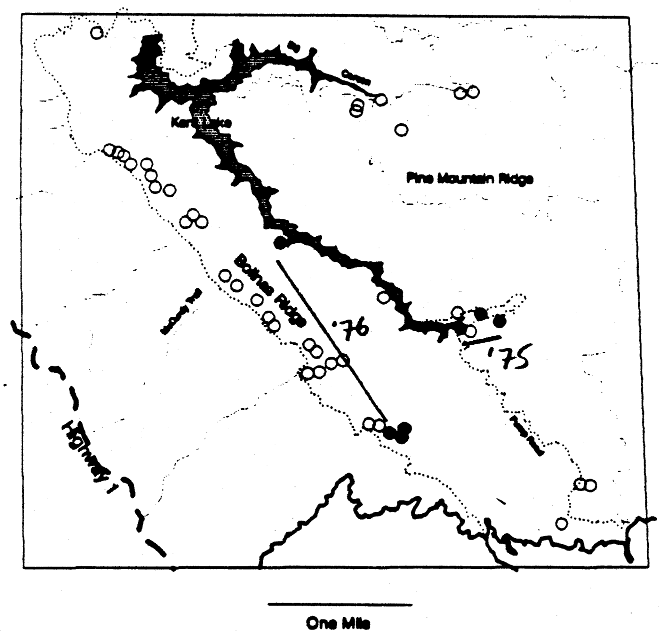
Fire Dates: 1890



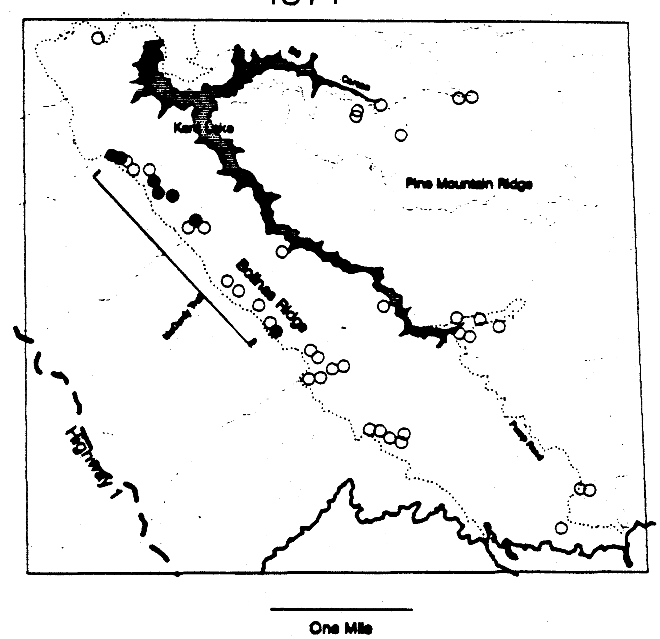
Fire Dates: 1885; 86



Fire Dates: 1875; 76

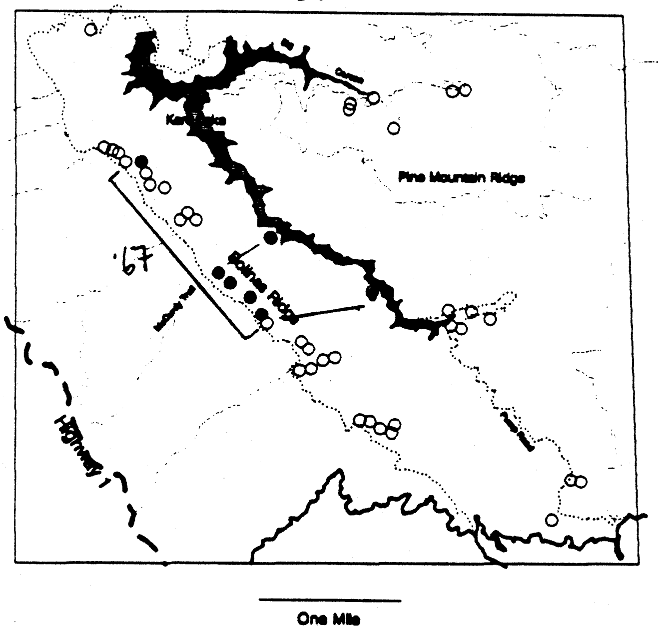


Fire Dates: 1871

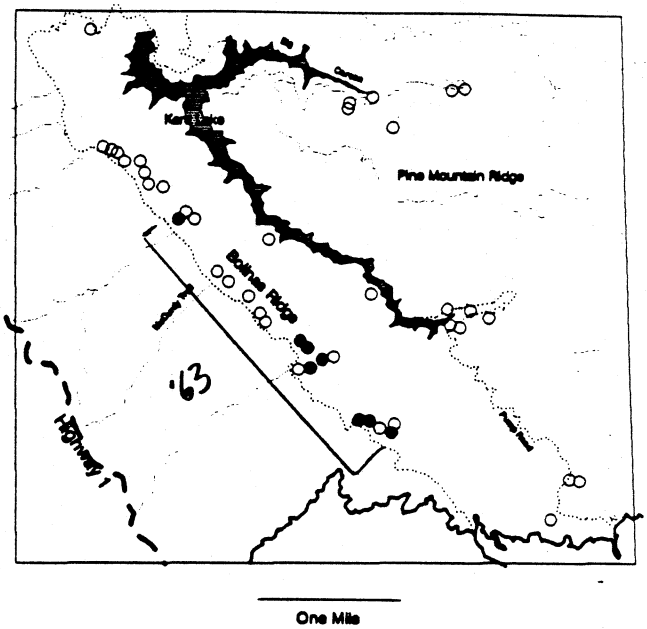


Marin County Municipal Watershed
Bolinas Ridge and Kent Lake

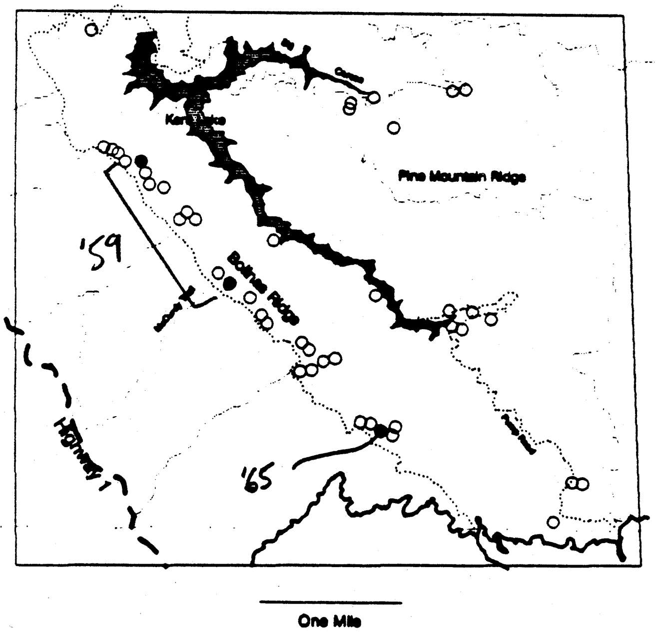
Fire Dates: 1867



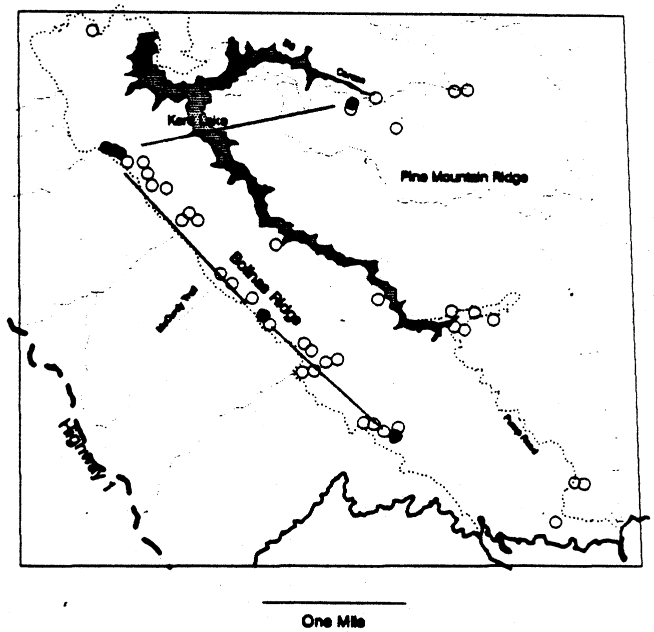
Fire Dates: spring 1863



Fire Dates: 1859; 65

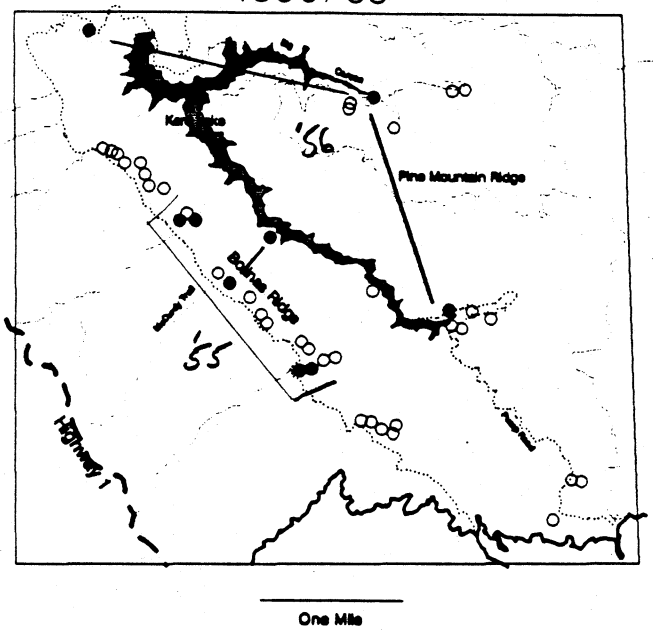


Fire Dates: spring 1857

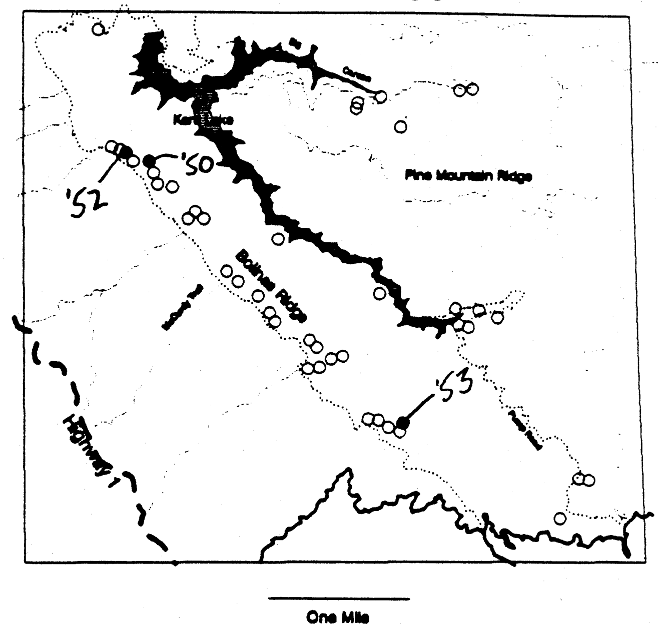


Marin County Municipal Watershed
Bolinas Ridge and Kent Lake

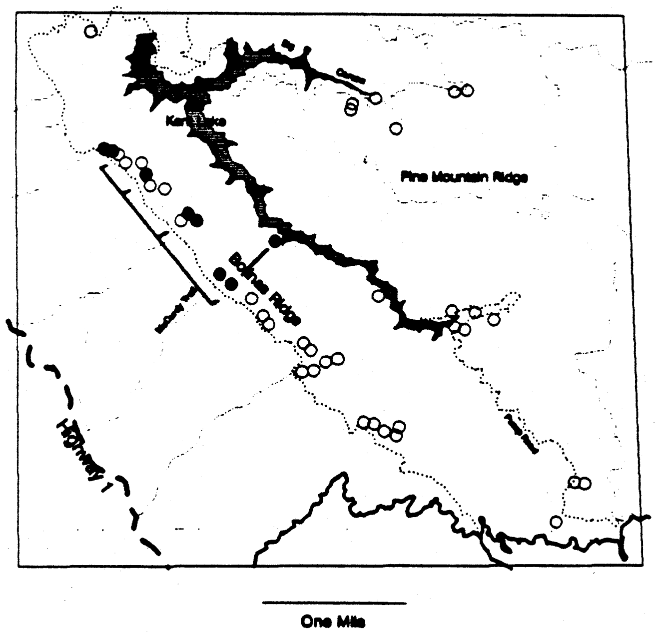
Fire Dates: 1856; 55



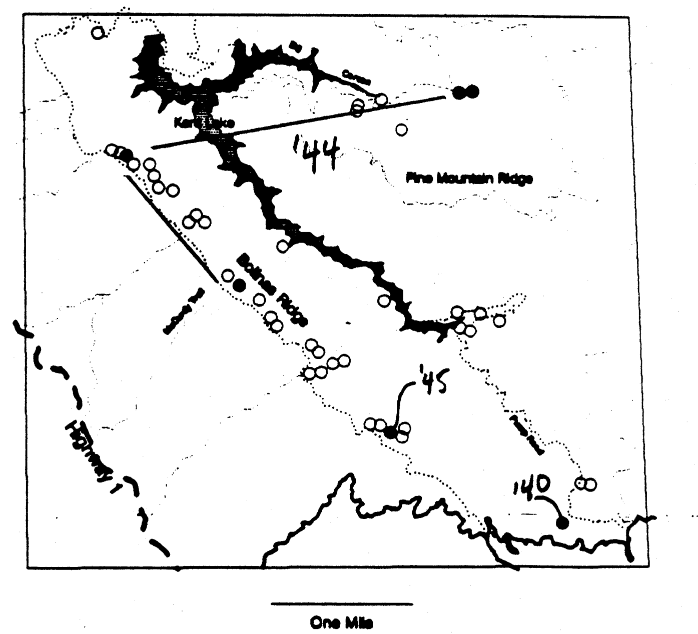
Fire Dates: 1853;52; 50



Fire Dates: 1848

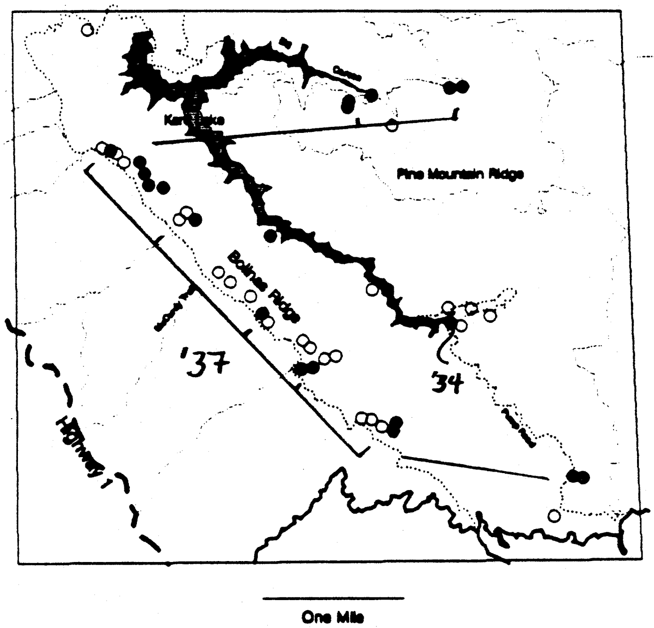


Fire Dates: 1844; 45; 40

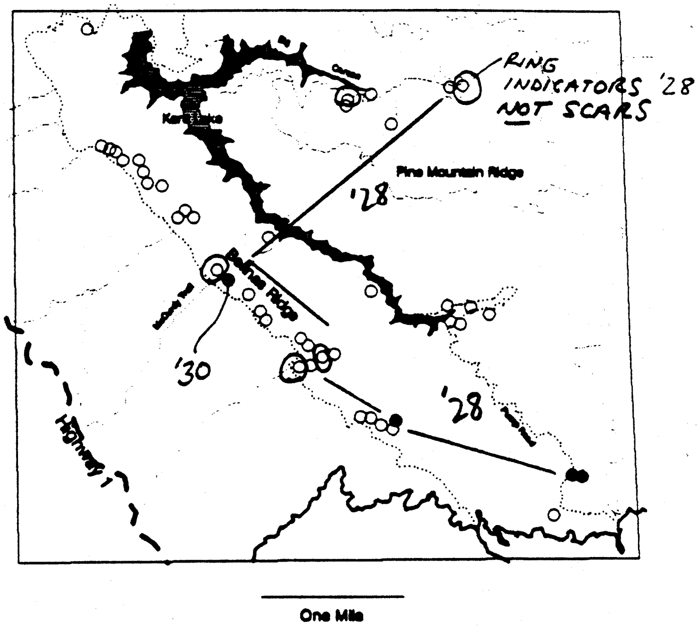


Marin County Municipal Watershed
Bolinas Ridge and Kent Lake

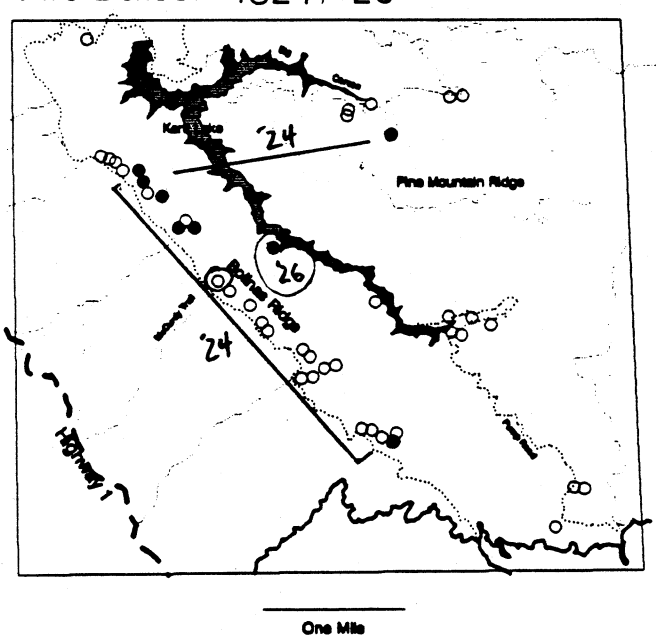
Fire Dates: 1837; 34



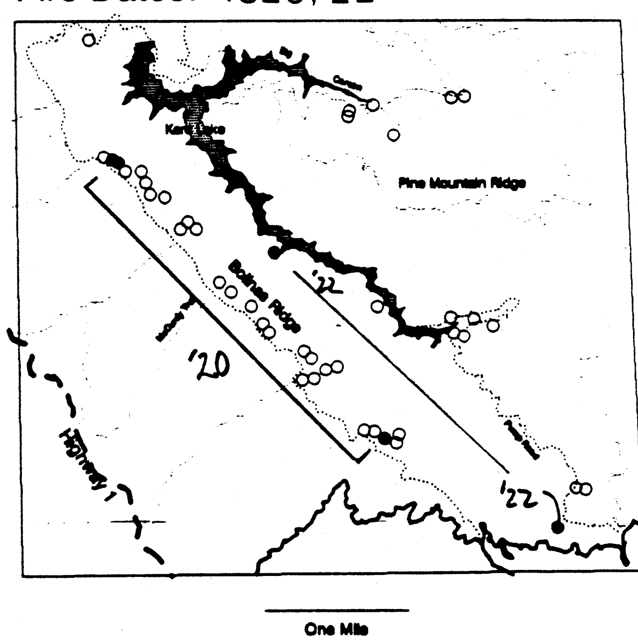
Fire Dates: 1828; 30



Fire Dates: 1824; 26

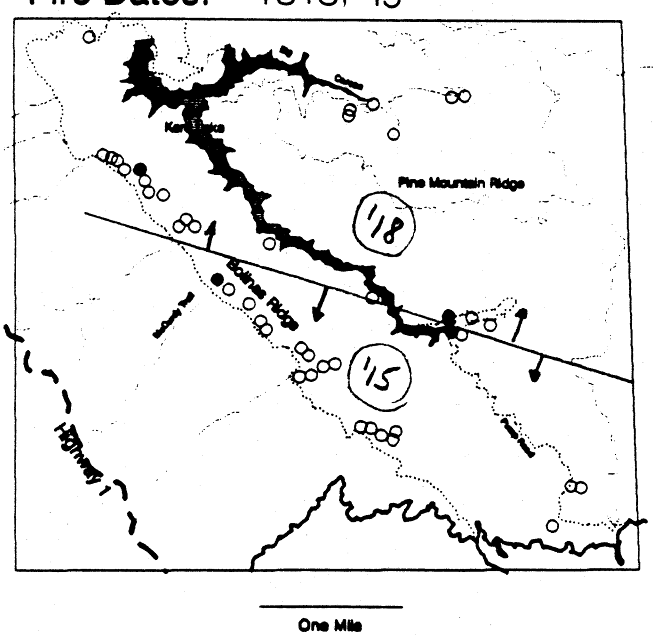


Fire Dates: 1820; 22

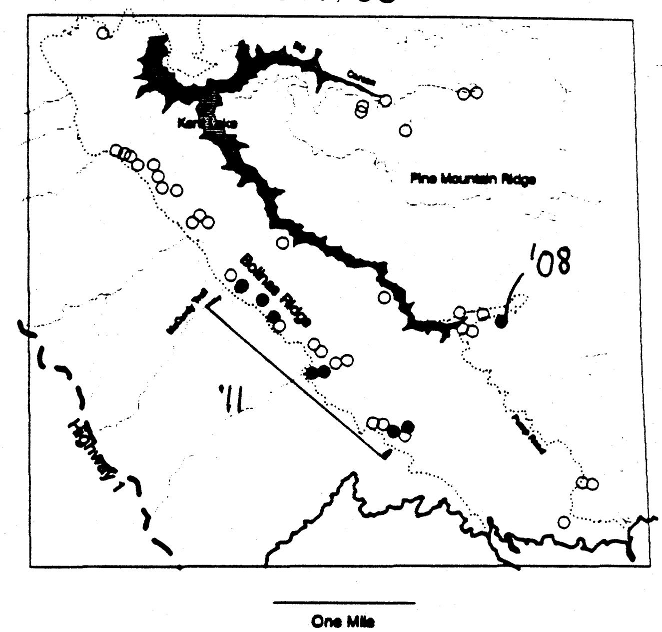


Marin County Municipal Watershed
Bolinas Ridge and Kent Lake

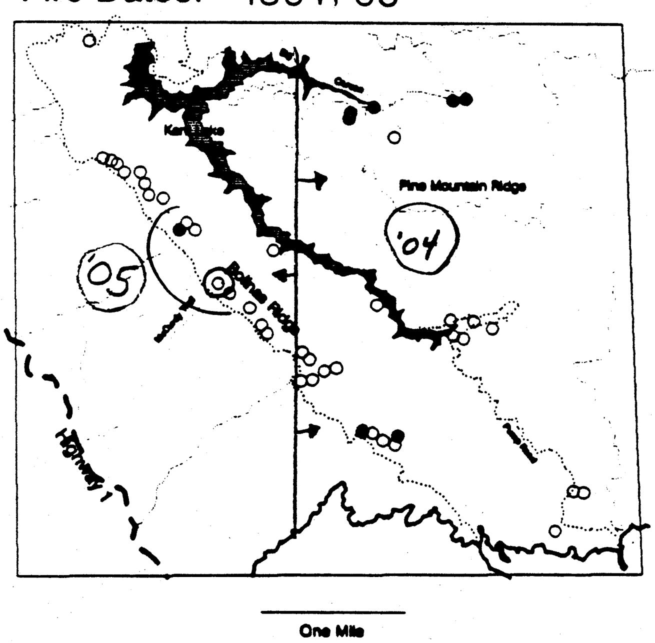
Fire Dates: 1818; 15



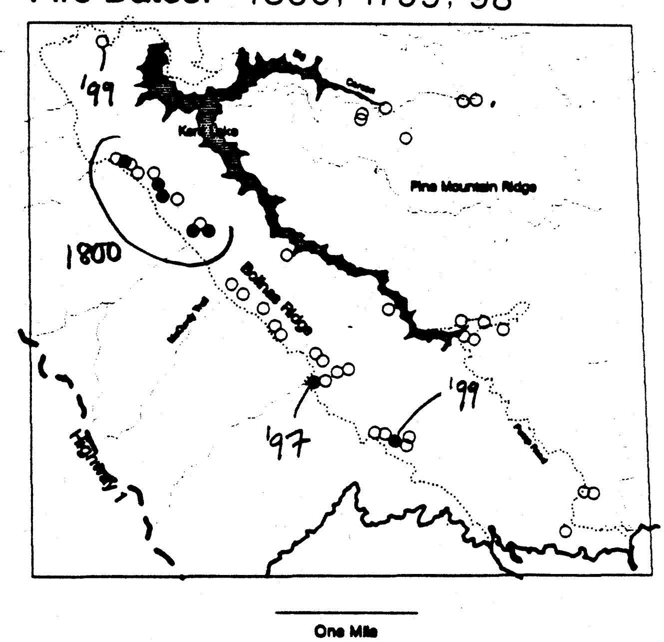
Fire Dates: 1811; 08



Fire Dates: 1804; 05



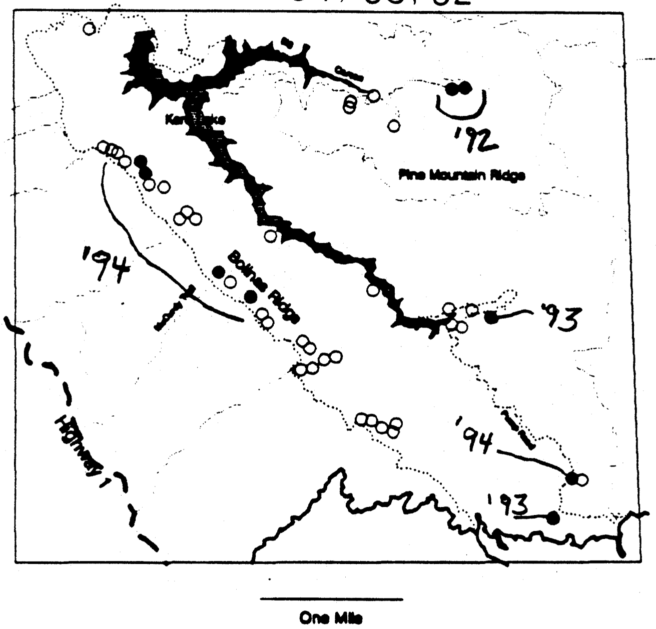
Fire Dates: 1800; 1799; 98



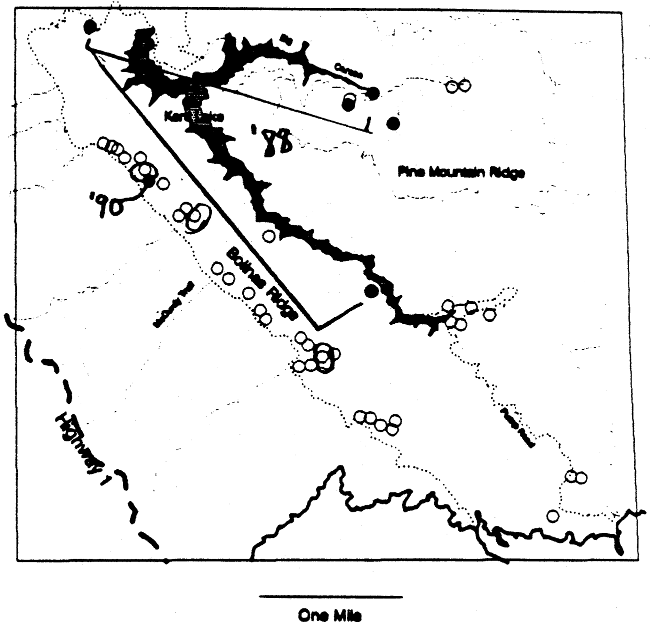
N

Marin County Municipal Watershed
Bolinas Ridge and Kent Lake

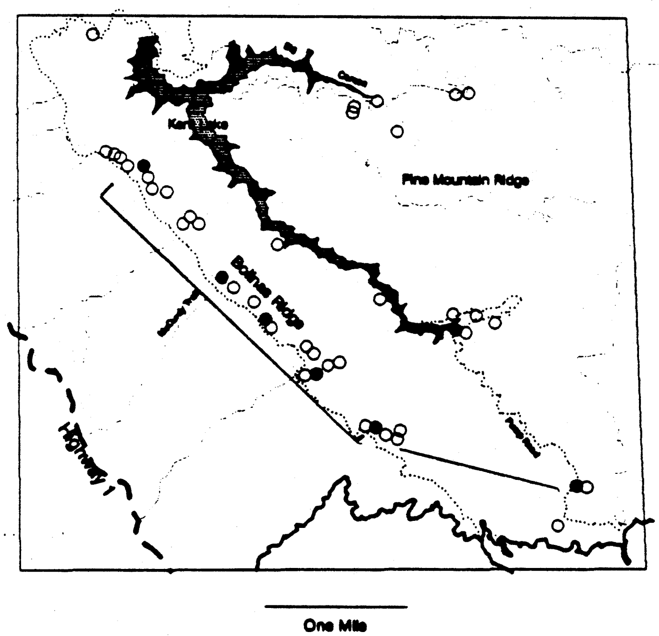
Fire Dates: 1794; 93; 92



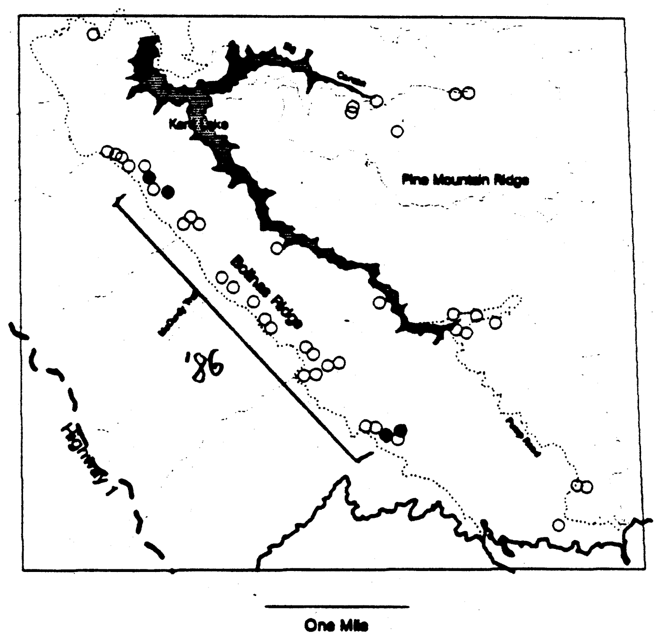
Fire Dates: 1790; 88



Fire Dates: spring 1787

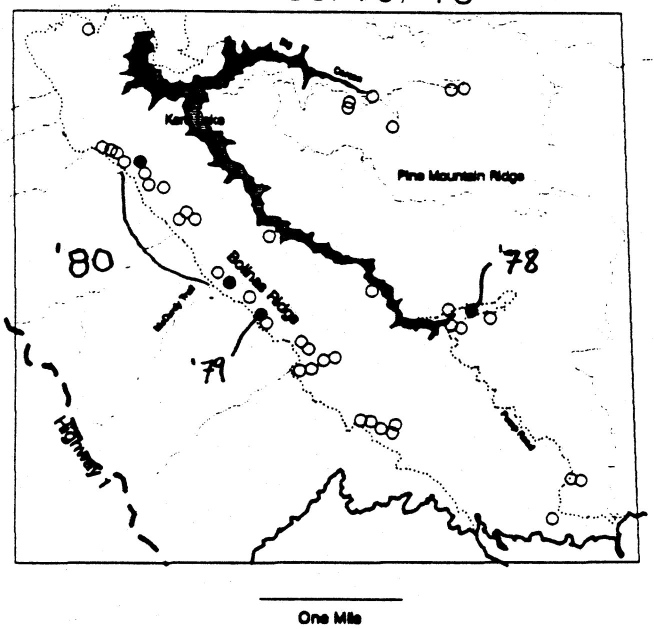


Fire Dates: 1786

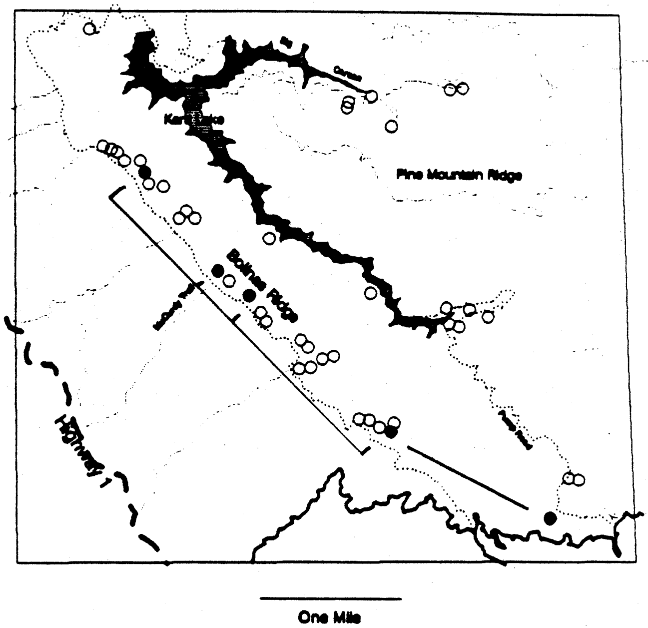


Marin County Municipal Watershed
Bolinas Ridge and Kent Lake

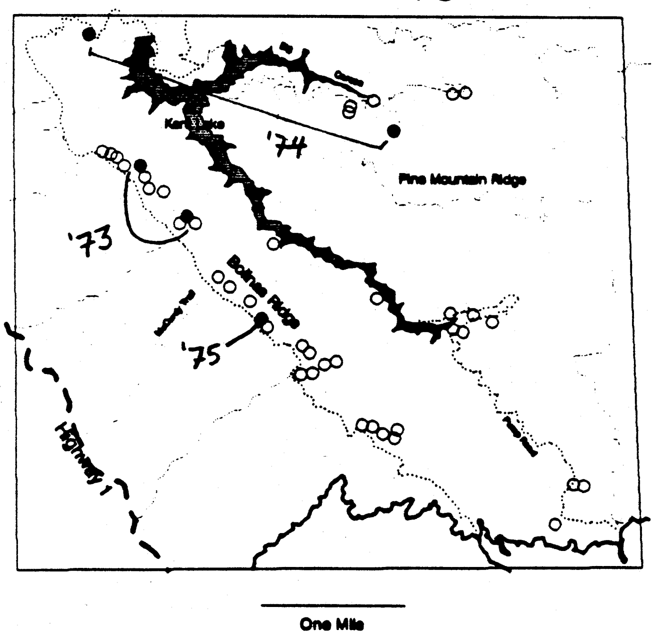
Fire Dates: 1780; 79; 78



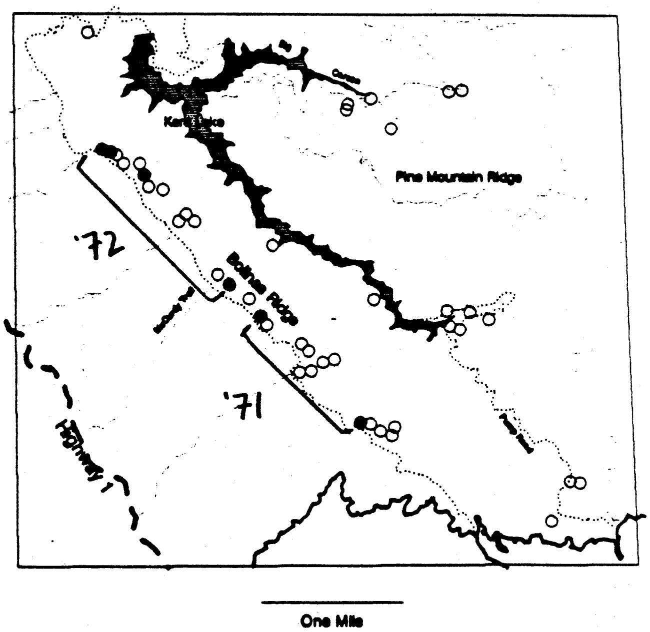
Fire Dates: 1776



Fire Dates: 1775; 74; 73



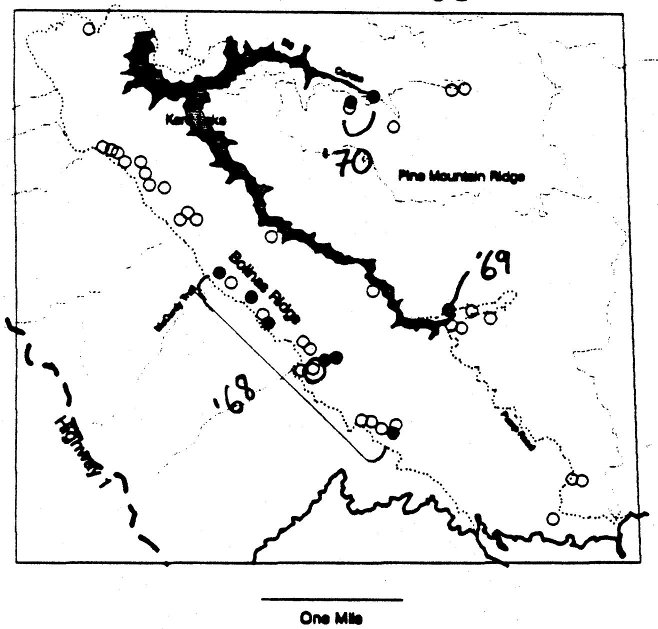
Fire Dates: 1772; 71



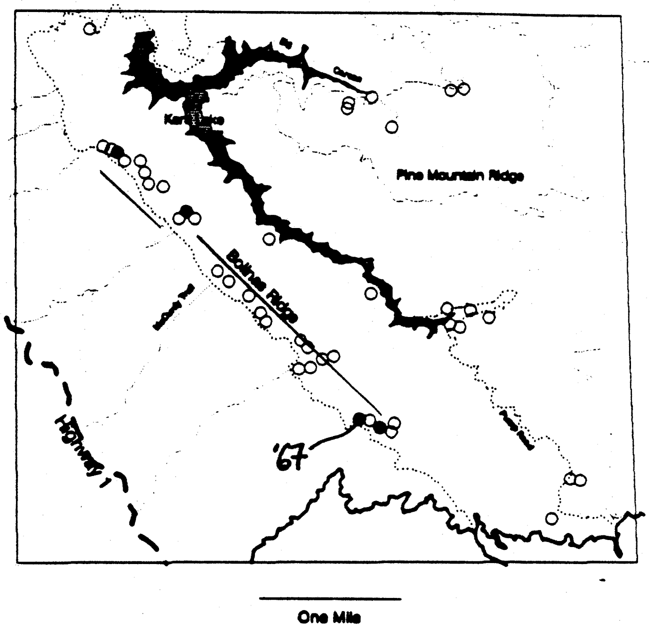
Marin County Municipal Watershed
Bolinas Ridge and Kent Lake

N

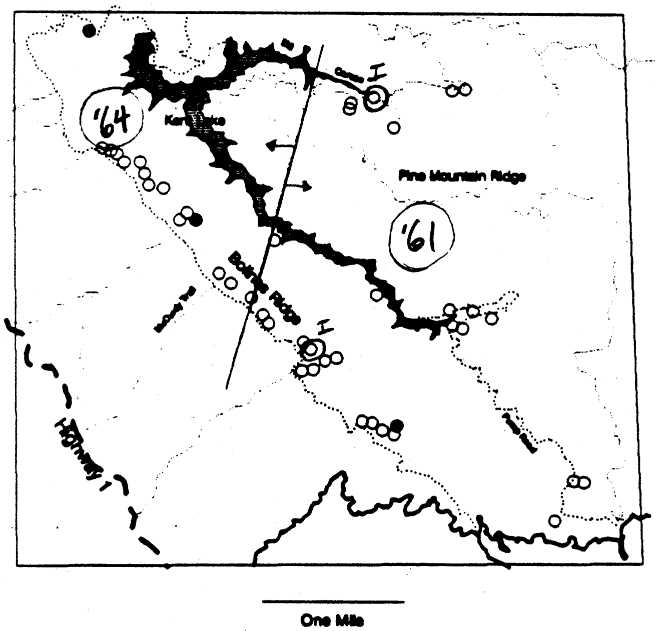
Fire Dates: 1770; 69; 68



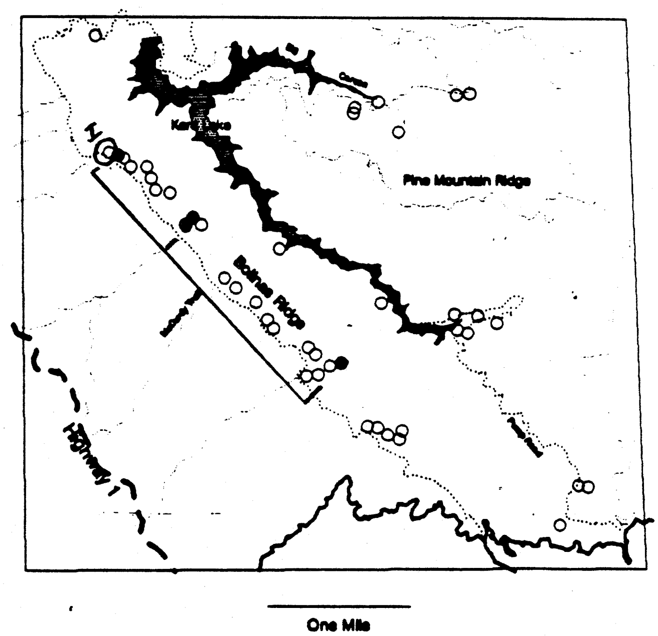
Fire Dates: 1767; 66



Fire Dates: 1764; 61



Fire Dates: 1760



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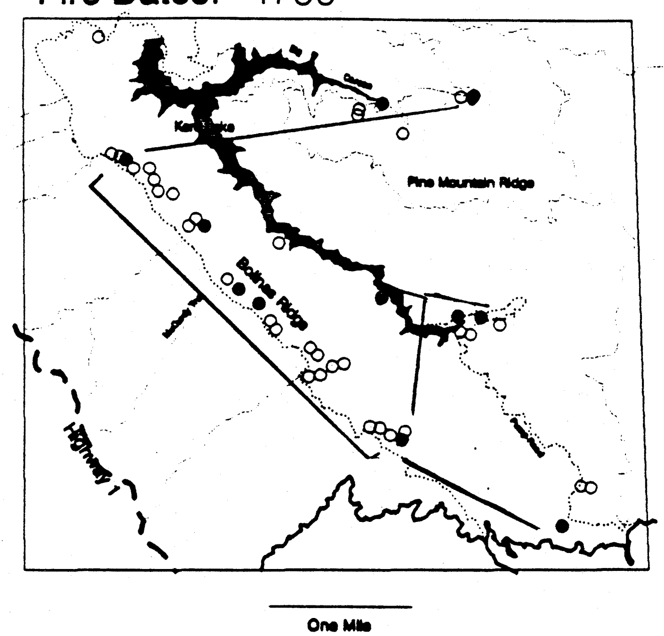
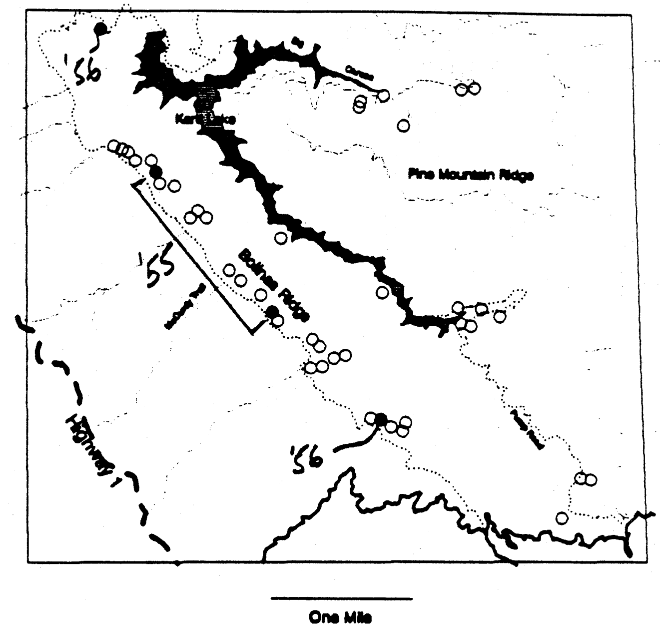
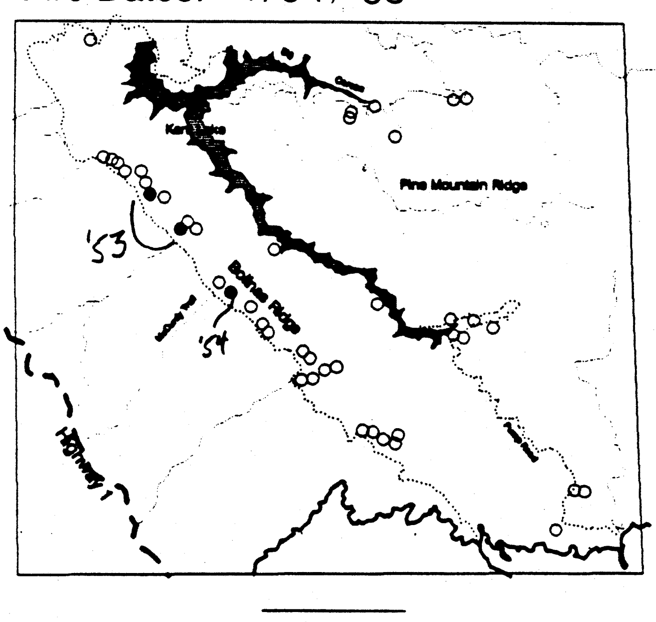
Fire Dates: 1759



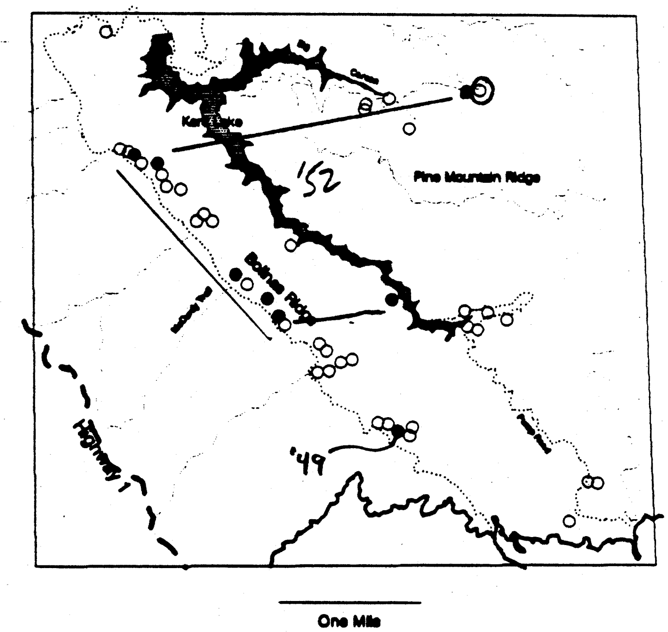
Fire Dates: 1756; 55



Fire Dates: 1754; 53



Fire Dates: 1752; 49



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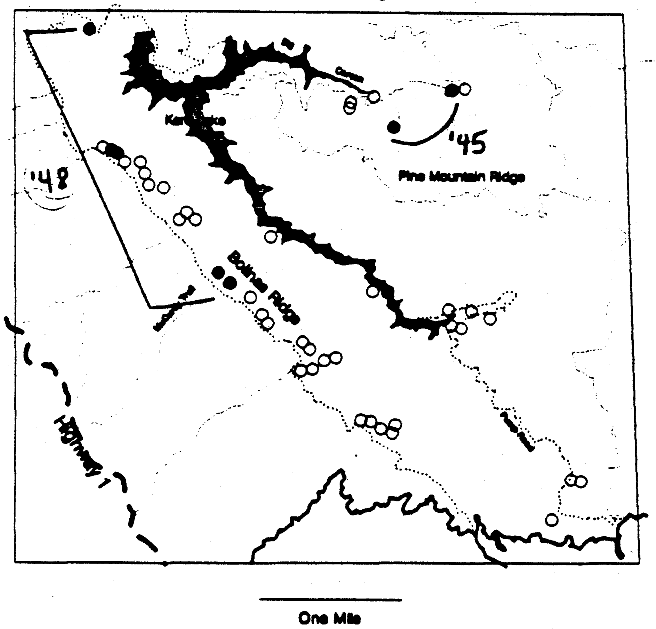
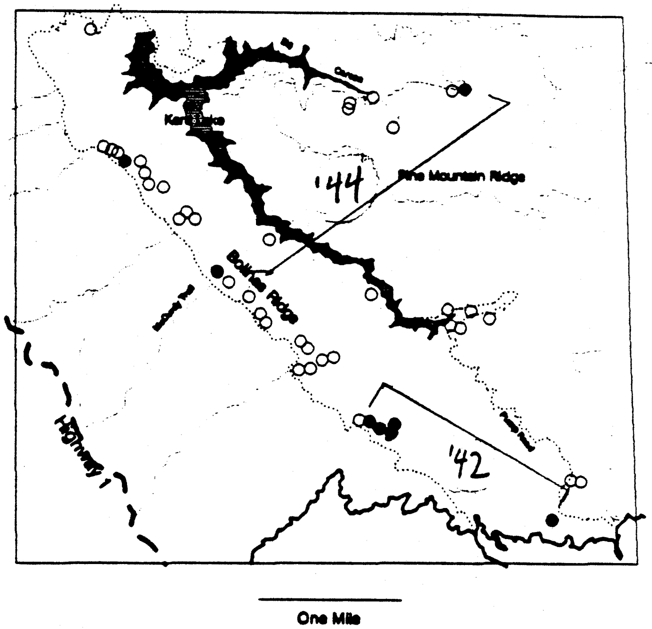
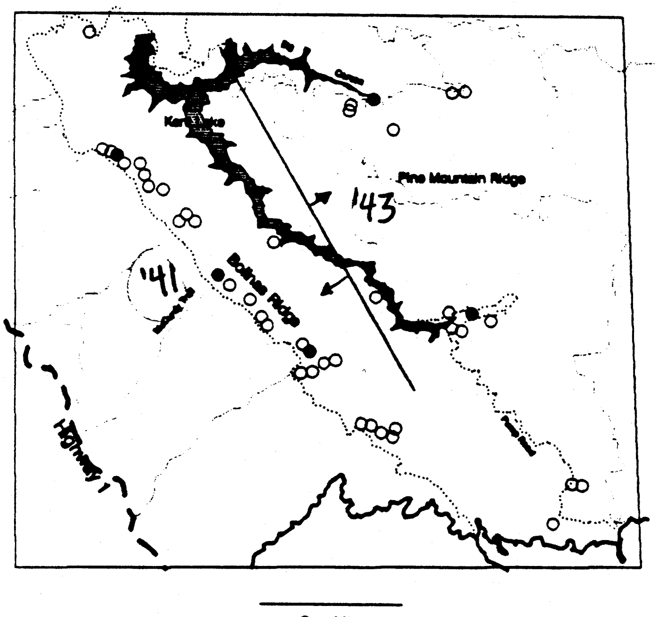
Fire Dates: 1748; 45



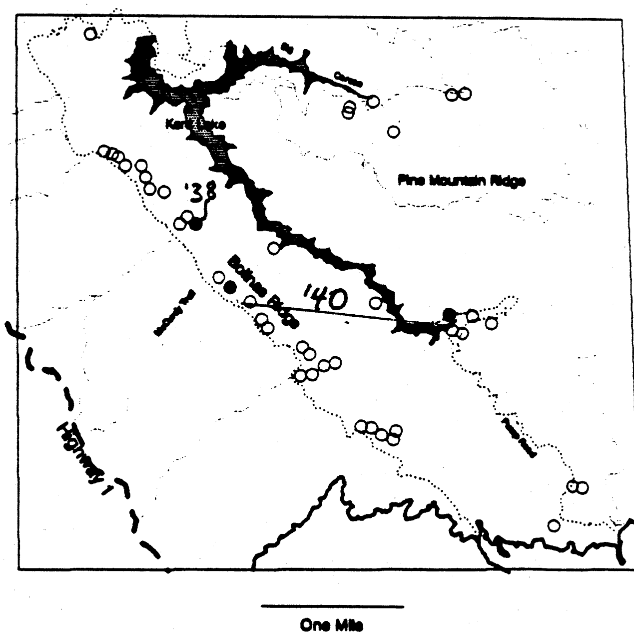
Fire Dates: 1744; 42



Fire Dates: 1743; 41



Fire Dates: 1740; 38



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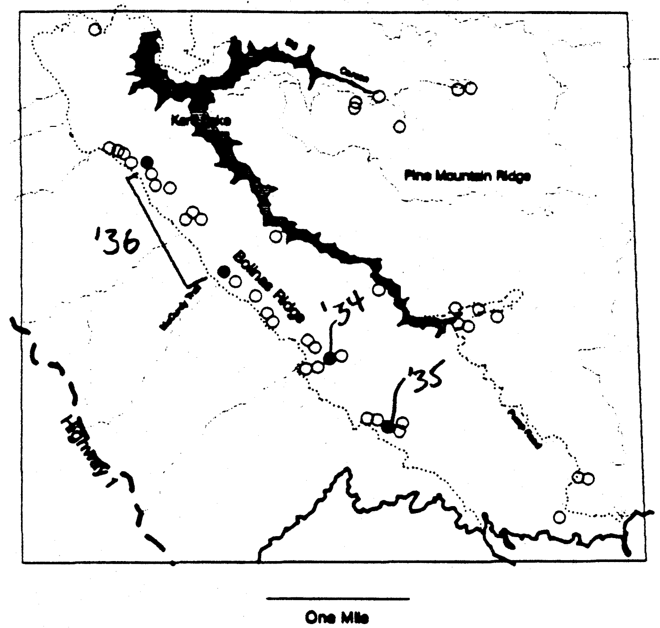
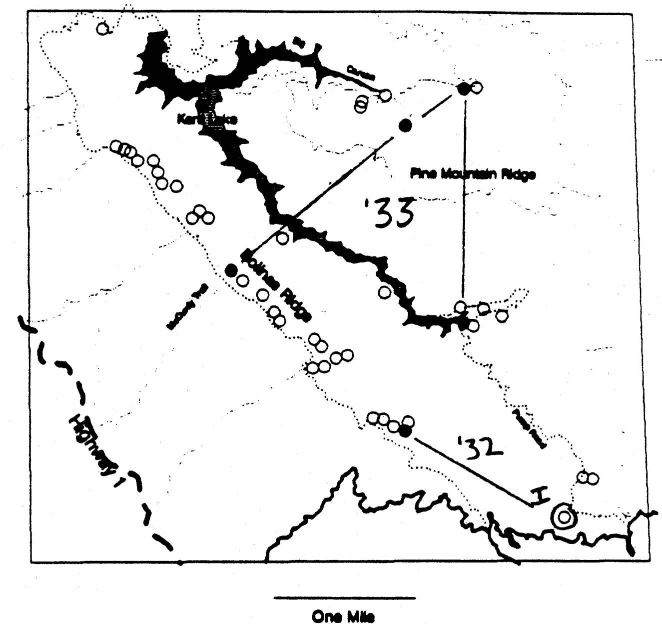
Marin County Municipal Watershed
Bolinas Ridge and Kent Lake

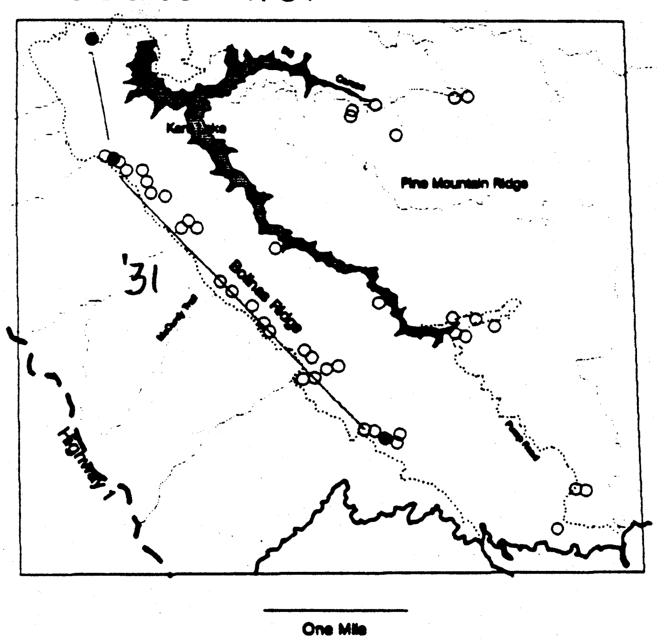
Fire Dates: 1736; 35; 34



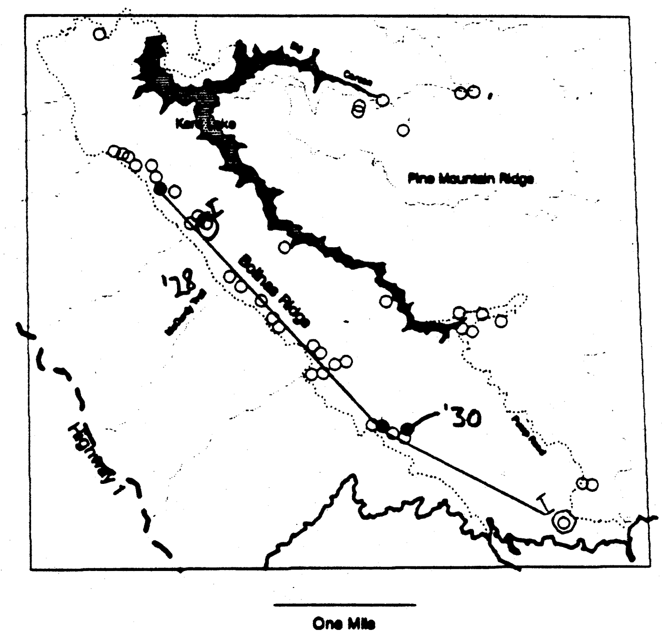
Fire Dates: 1733; 32



Fire Dates: 1731



Fire Dates: 1730; 28



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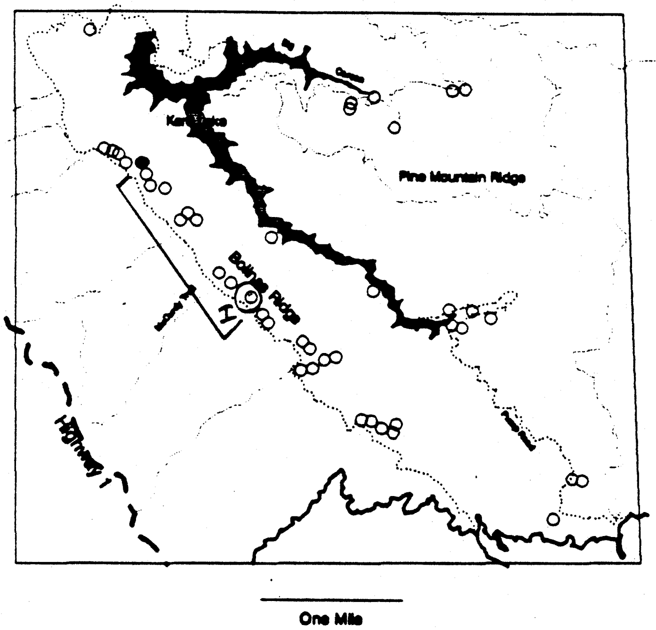
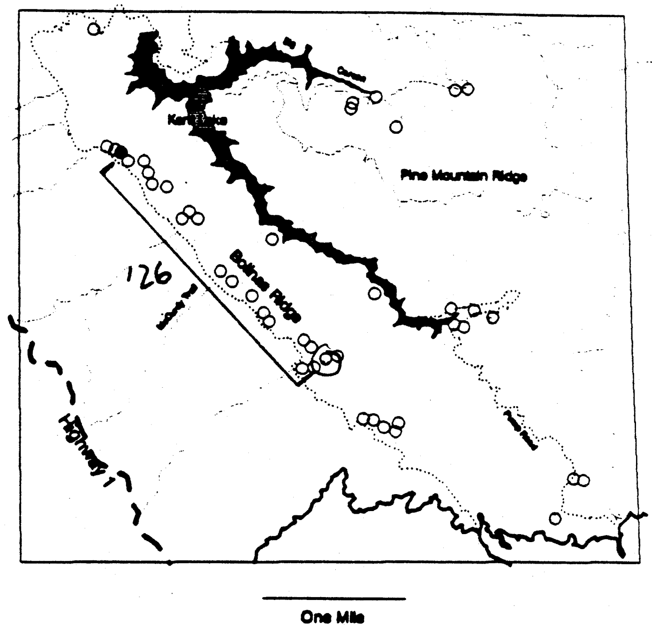
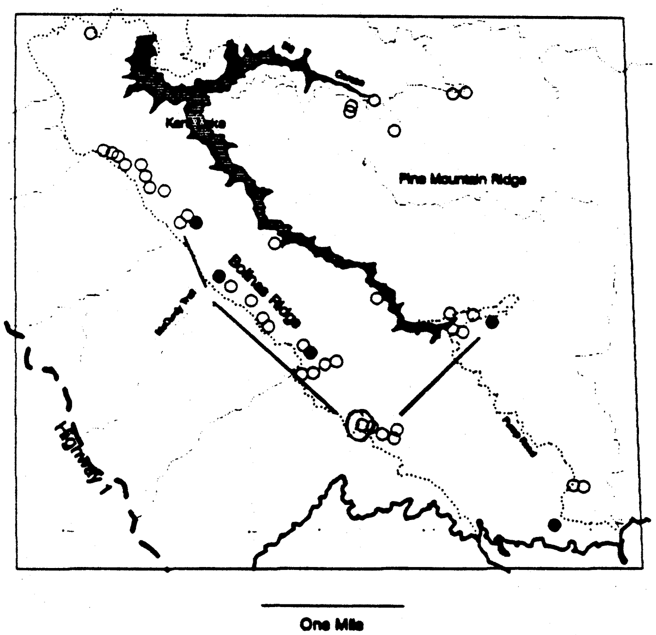
Fire Dates: 1727



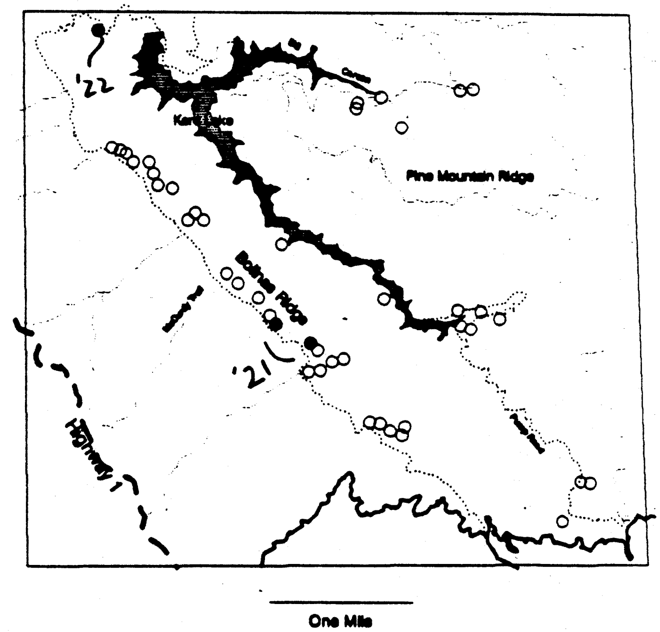
Fire Dates: 1726



Fire Dates: 1724



Fire Dates: 1722; 21



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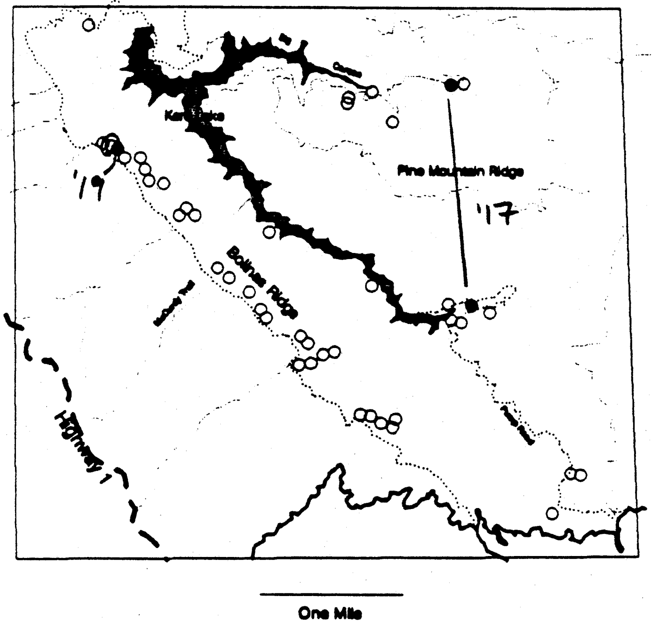
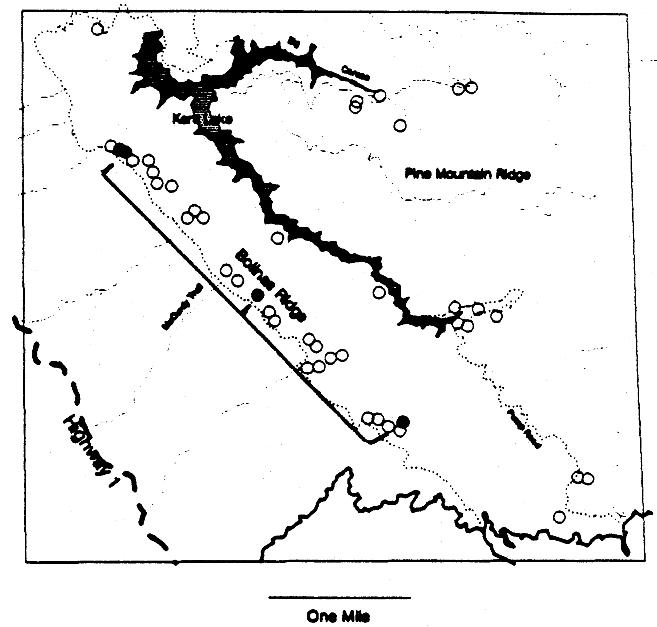
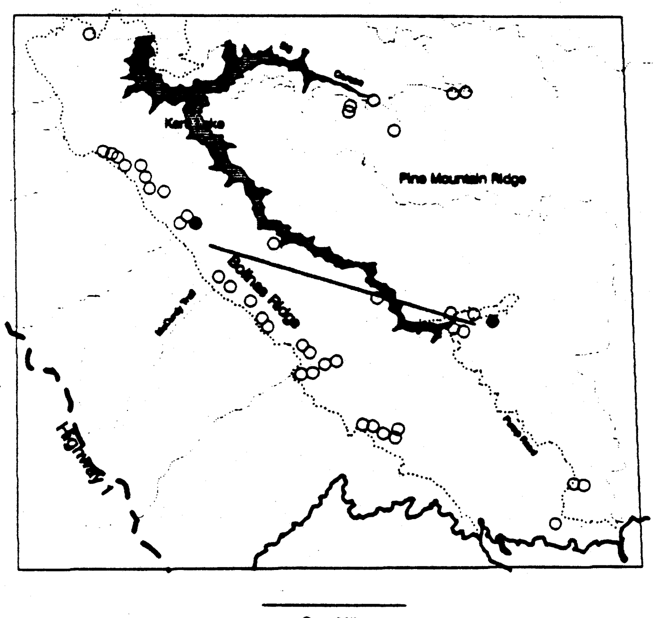
Fire Dates: 1719; 17



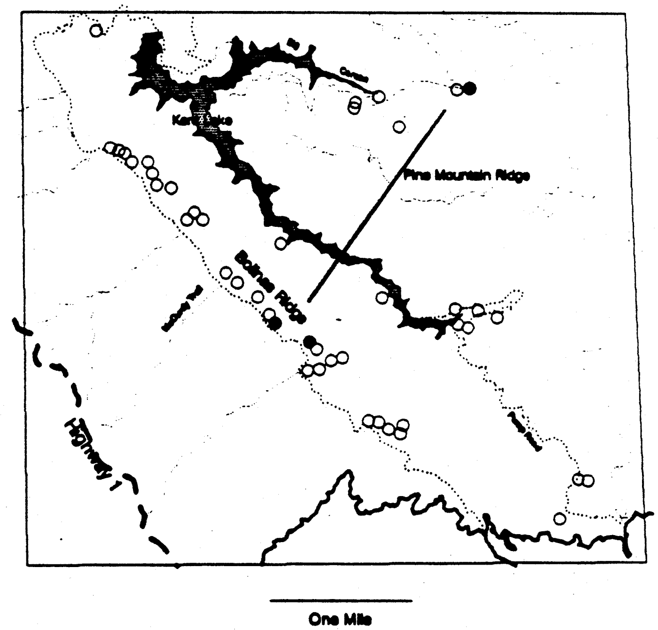
Fire Dates: 1715



Fire Dates: 1713



Fire Dates: 1712



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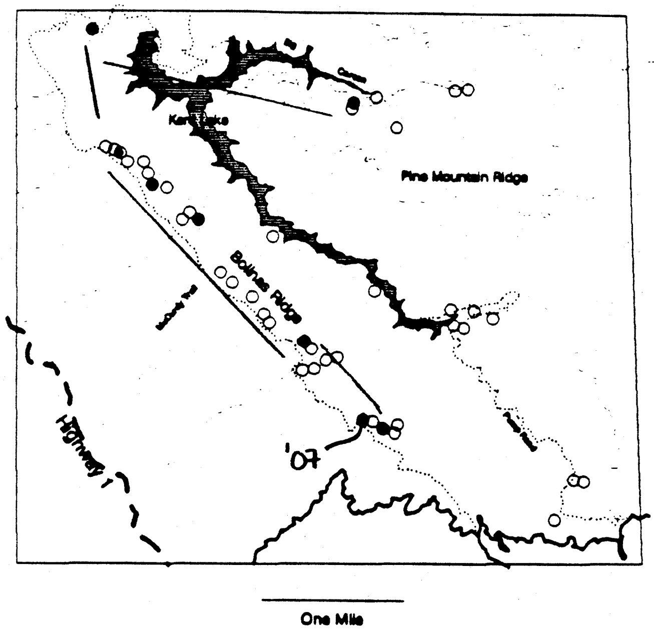
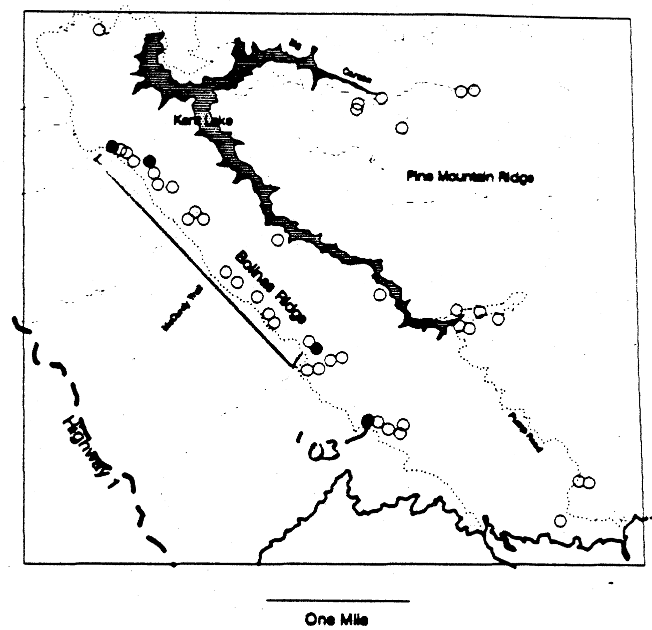
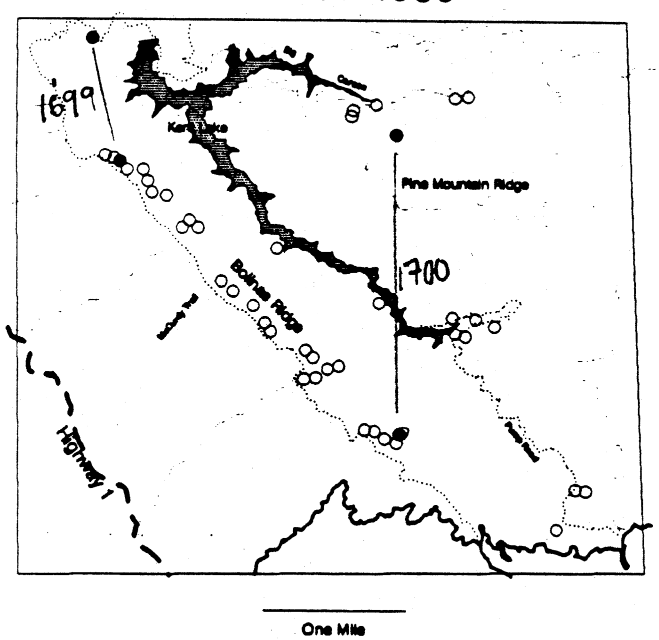
Fire Dates: 1708; 07



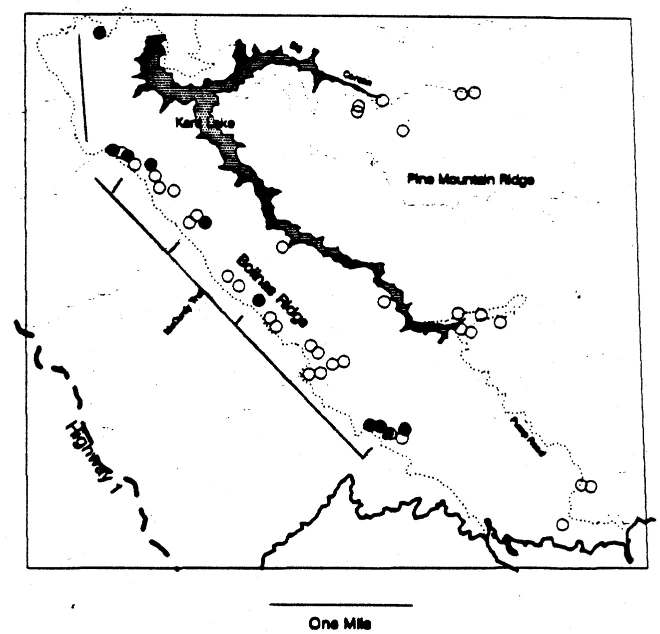
Fire Dates: 1705; 03



Fire Dates: 1700; 1699



Fire Dates: 1693



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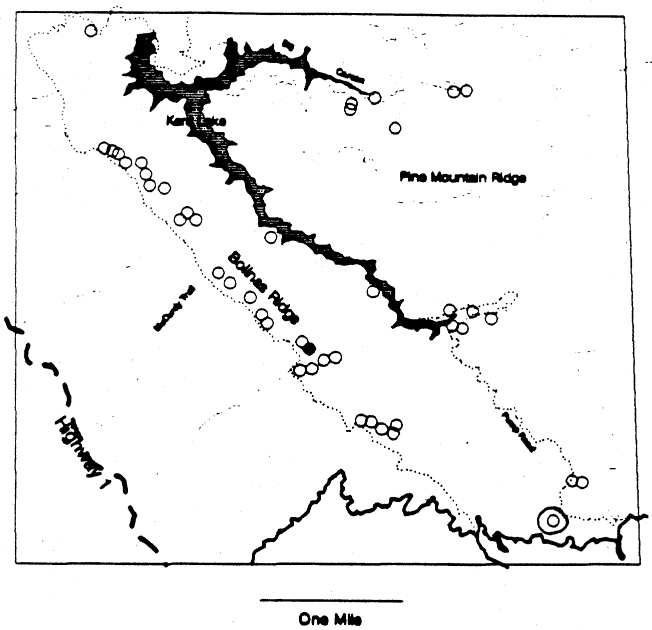
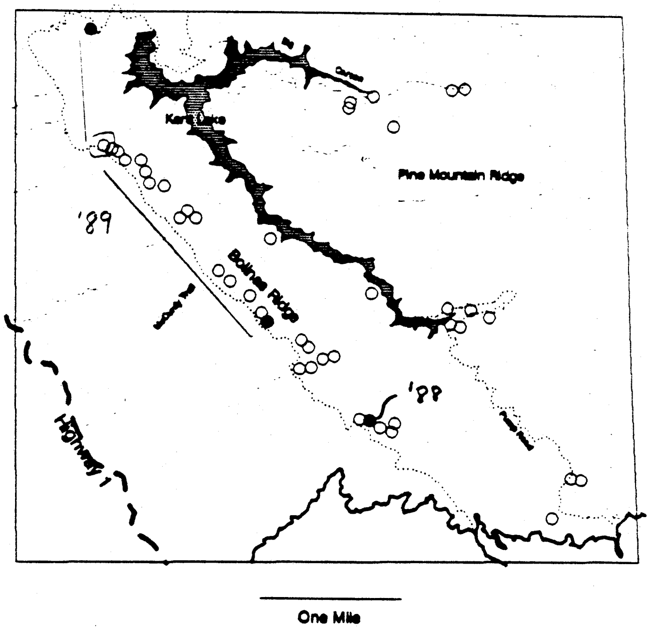
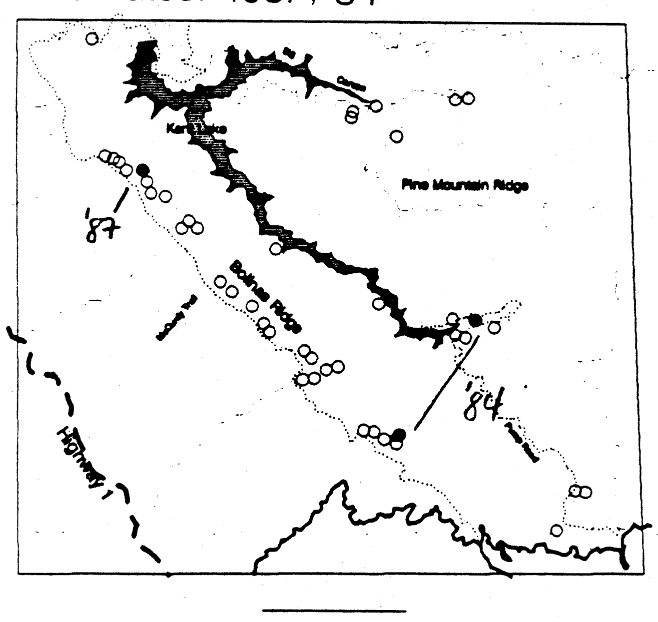
Fire Dates: 1692



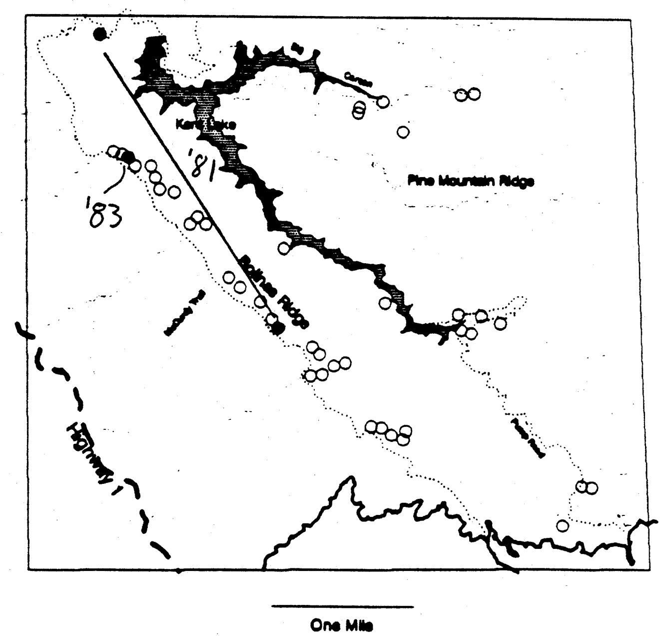
Fire Dates: 1689; 88



Fire Dates: 1687; 84



Fire Dates: 1683; 81



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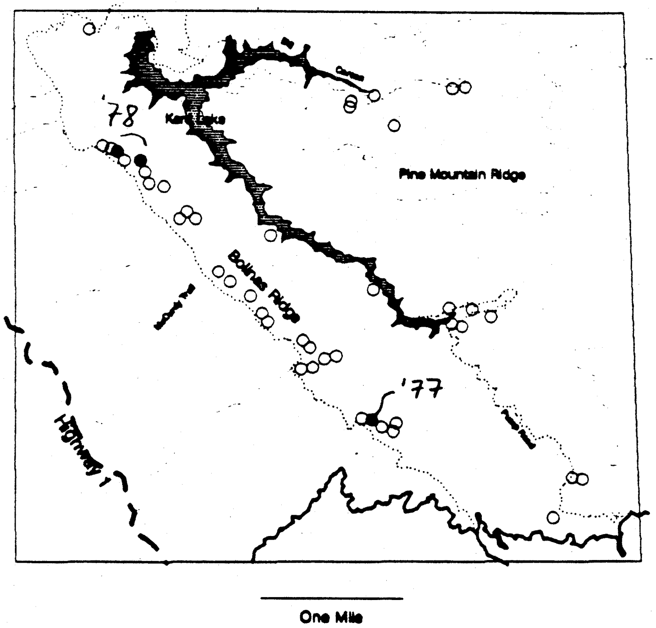
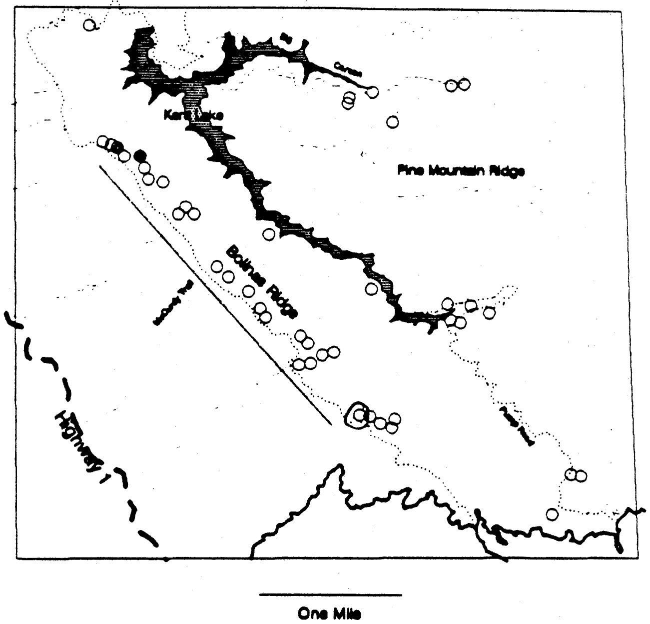
Bolinas Ridge and Kent Lake

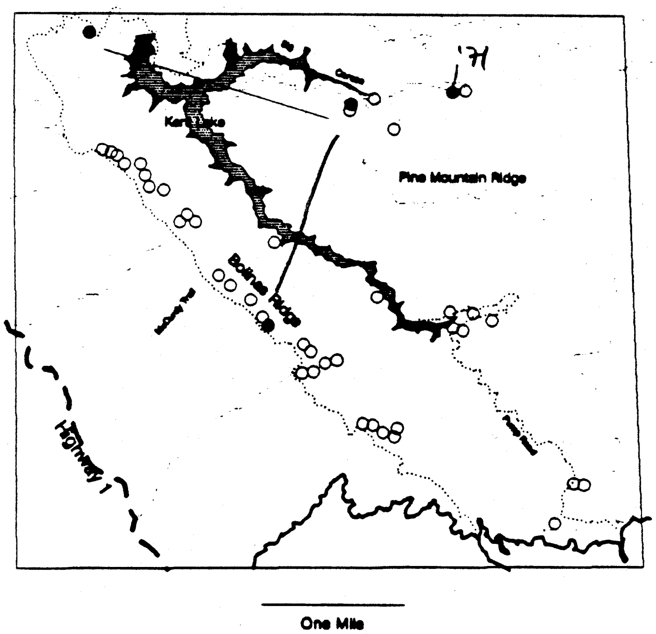
Fire Dates: 1678; 77



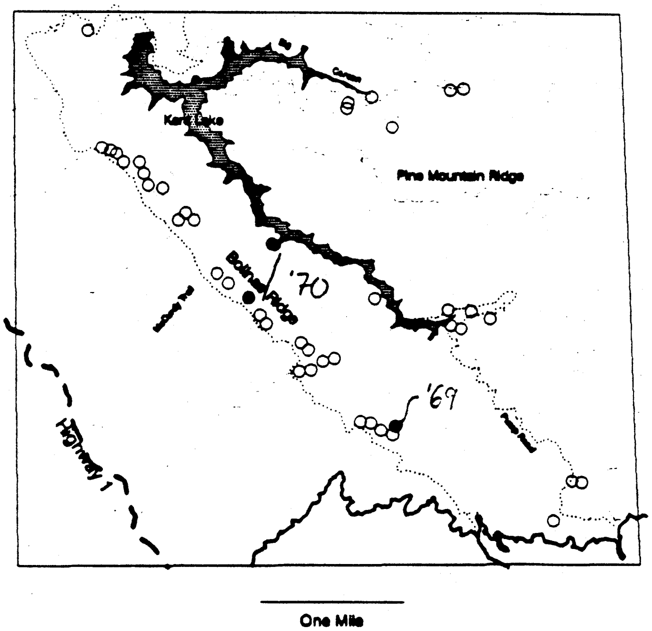
Fire Dates: 1673



Fire Dates: 1672; 71



Fire Dates: 1670; 69



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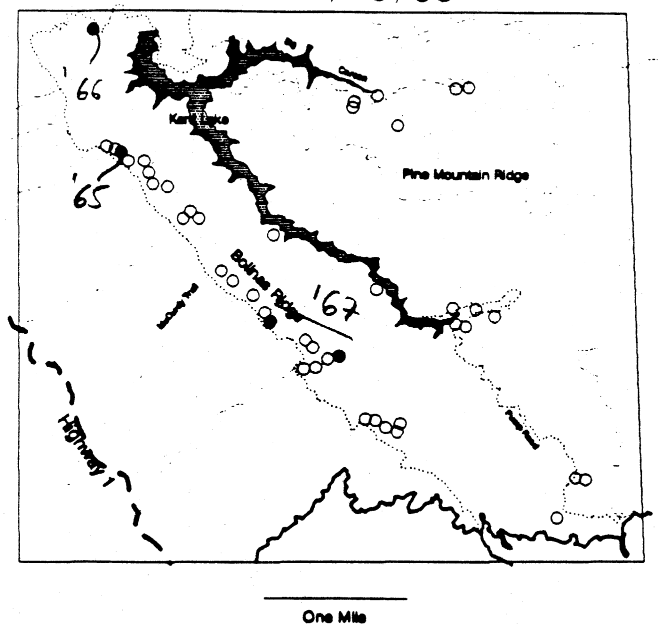
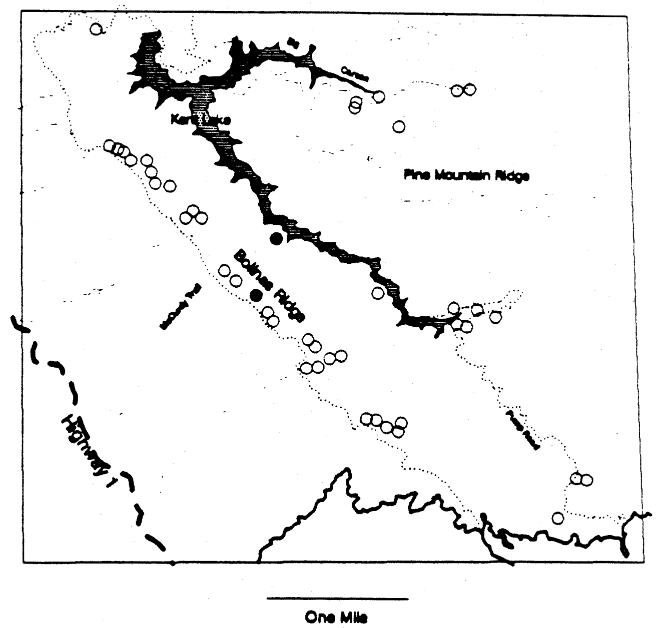
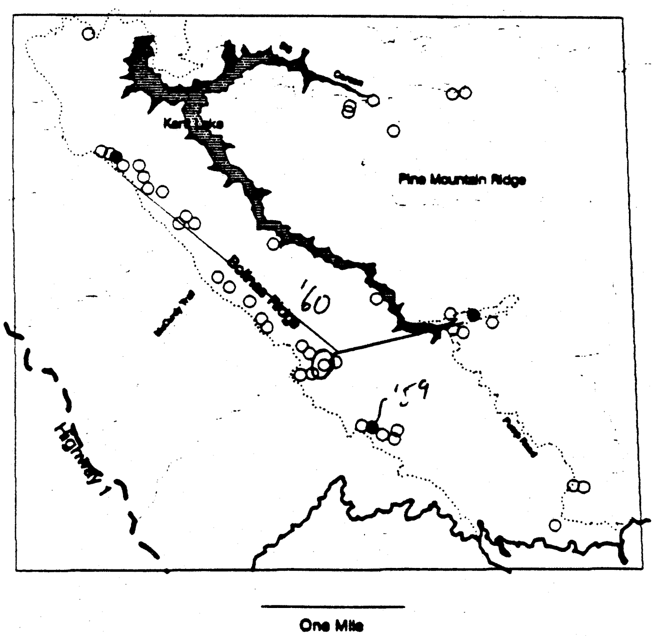
Fire Dates: 1667; 66; 65



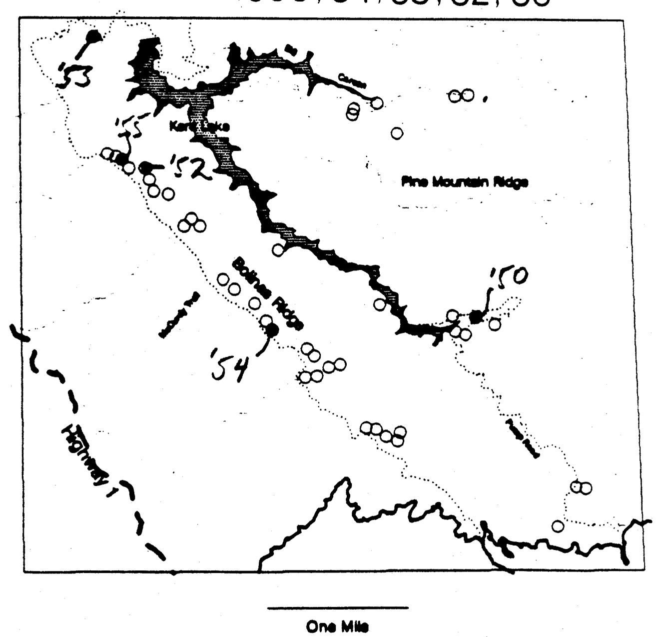
Fire Dates: 1661



Fire Dates: 1660; 59



Fire Dates: 1655; 54; 53; 52; 50



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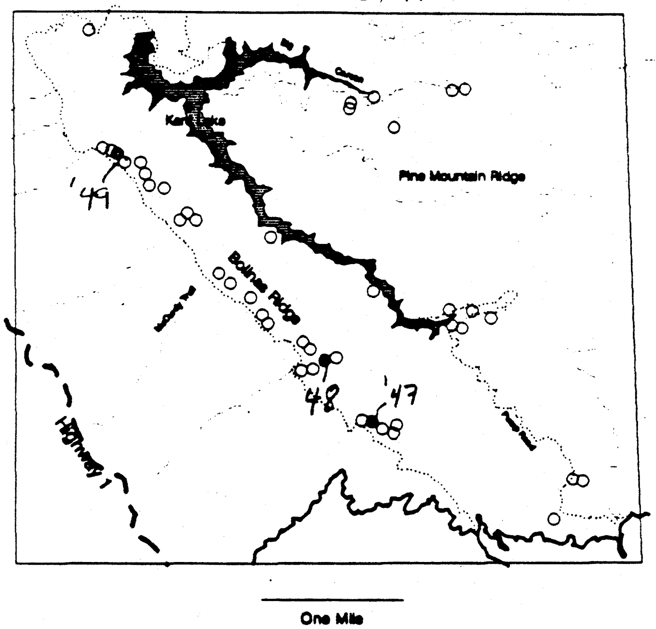
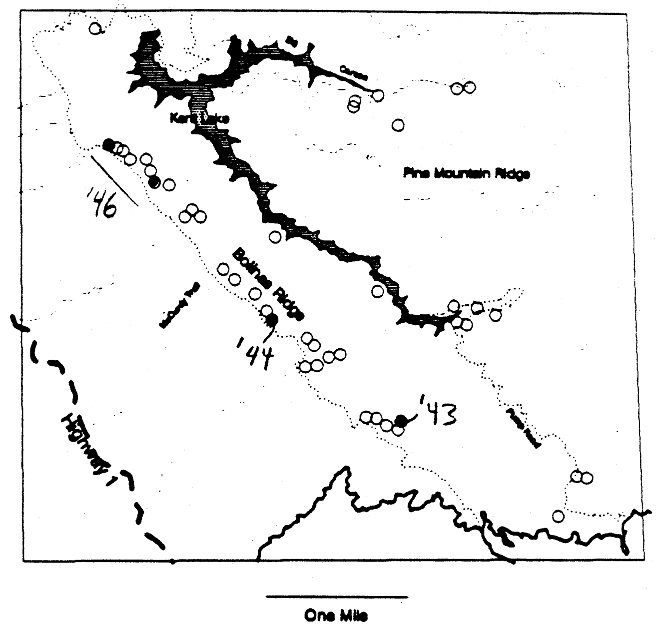
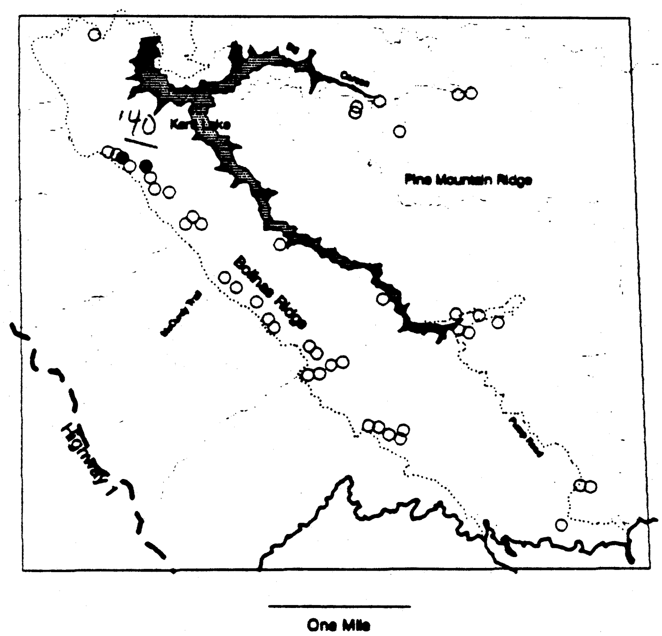
Fire Dates: 1649; 48; 47



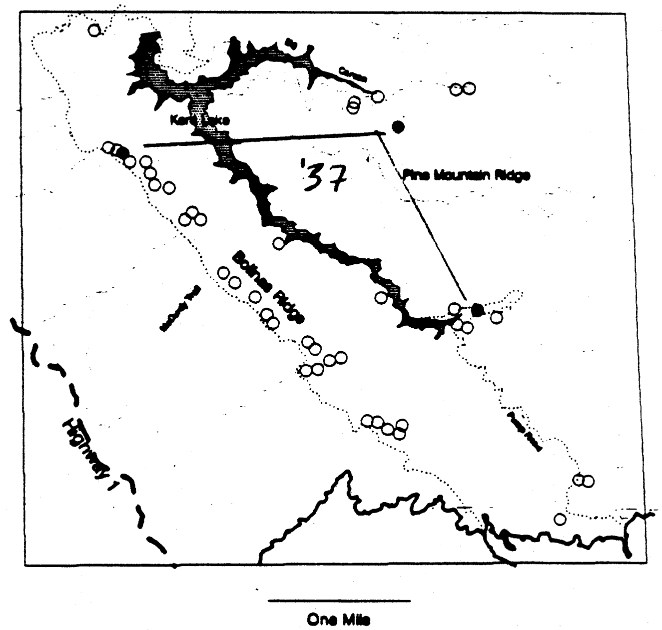
Fire Dates: 1646; 44; 43



Fire Dates: 1640



Fire Dates: 1637



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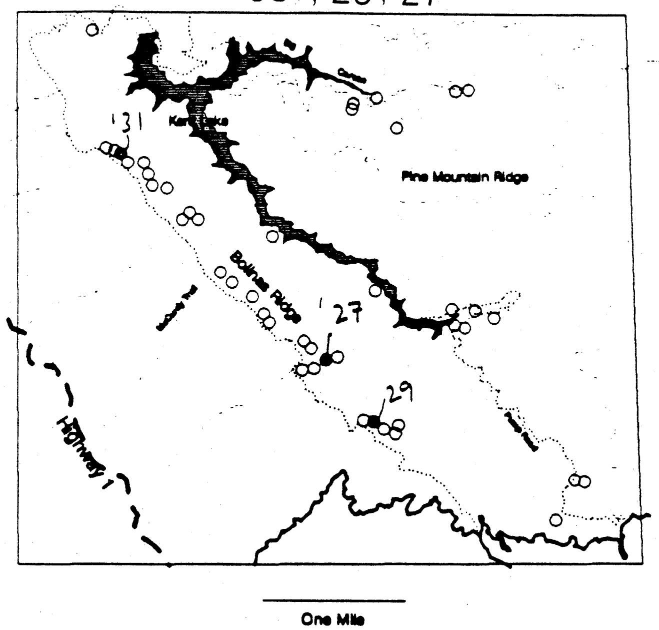
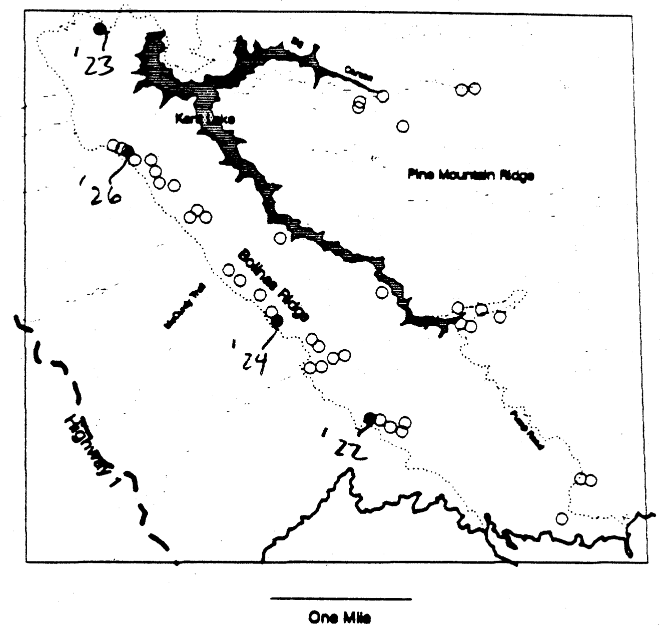
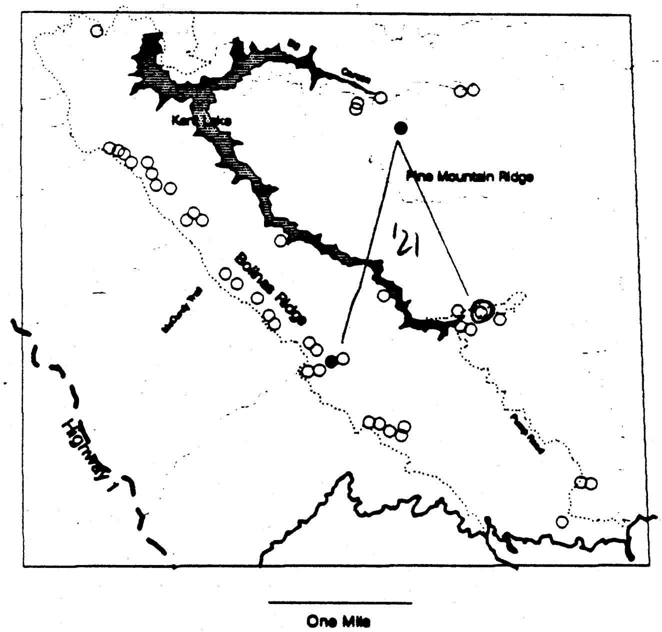
Fire Dates: 1631; 29; 27



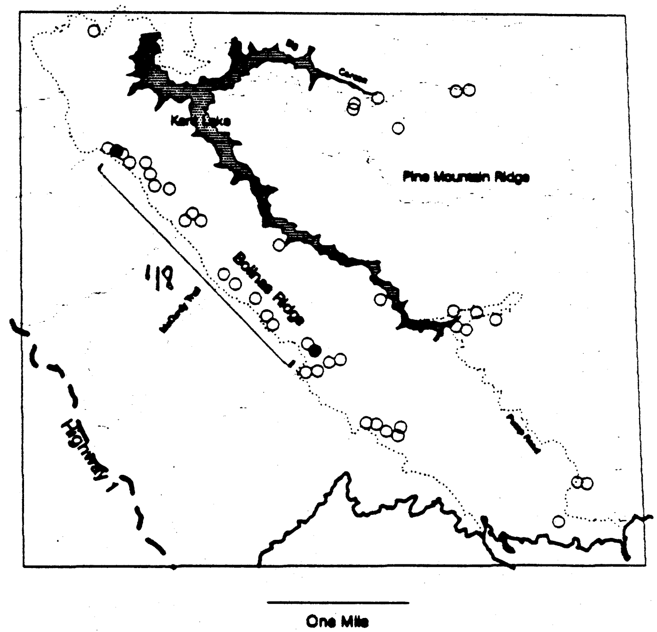
Fire Dates: 1626; 24; 23; 22



Fire Dates: 1621



Fire Dates: 1618



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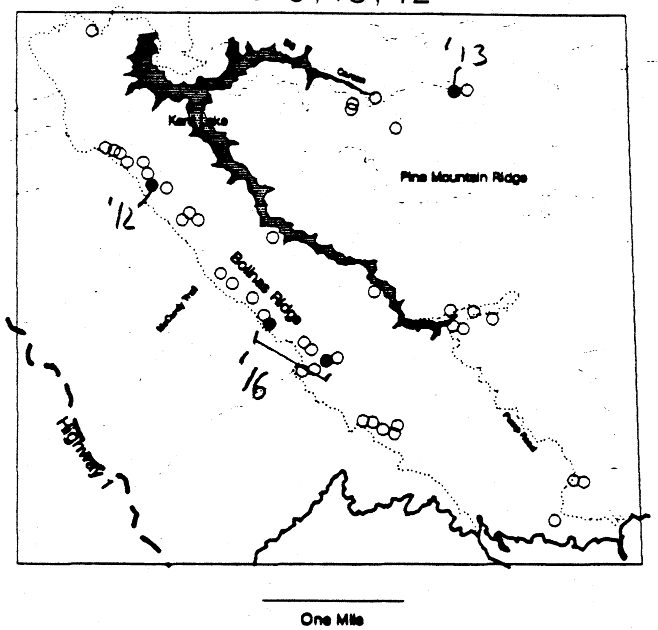
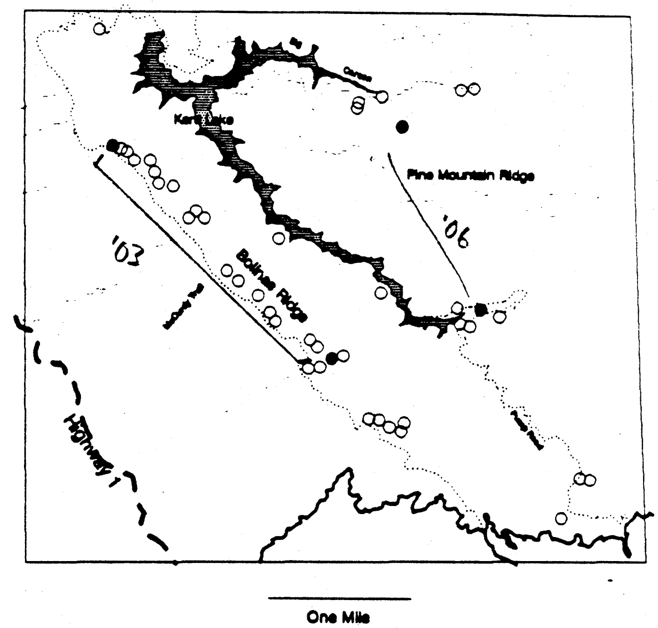
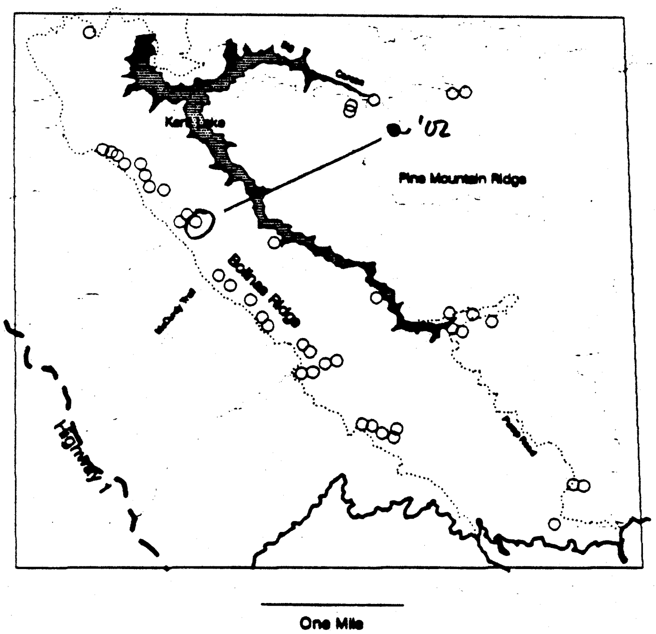
Fire Dates: 1616; 13; 12



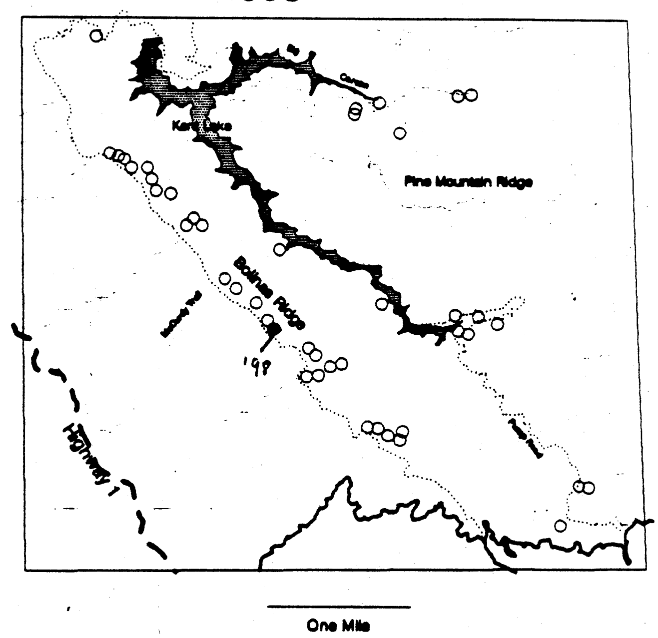
Fire Dates: 1606; 03



Fire Dates: 1602



Fire Dates: 1598



Appendix 3. Summary of mean composite fire intervals (years) and standard errors for paired composites. Xf represents average frequency of fire coincidence among composites.

I/II

	$\bar{X}$	SE	$\bar{X}f$
1904-1945	10.3	10.9	0.8
1850-1904	6.0	5.3	0.6
1800-1850	3.6	3.4	0.6
1752-1800	2.3	1.6	0.6
1701-1752	2.7	1.5	0.6
1650-1701	3.2	1.9	0.5
1602-1650	3.7	2.3	0.5
1559-1602	6.1	3.3	0.5
1502-1559	5.2	3.3	0.5
1399-1502	34.3	40.7	0.5

VI/VII

	$\bar{X}$	SE	$\bar{X}f$
1904-1945	13.7	11.9	1.0
1853-1904	5.1	4.4	0.5
1801-1853	3.5	2.4	0.5
1751-1801	3.1	2.1	0.5
1702-1751	3.3	1.7	0.6
1651-1702	4.6	3.4	0.5
1607-1651	4.9	2.4	0.5
1553-1607	7.7	6.0	0.5

V/VIII

	$\bar{X}$	SE	$\bar{X}f$
1904-1945	13.7	11.9	1.0
1853-1904	12.8	10.7	0.5
1811-1853	5.3	3.0	0.6
1759-1811	7.4	4.1	0.6
1703-1759	9.3	6.8	0.5
1648-1703	7.9	8.4	0.5
1600-1648	9.6	7.4	0.5
1552-1600	8.0	6.0	0.5

VI/VIII

	$\bar{X}$	SE	$\bar{X}f$
1904-1945	13.7	11.9	1.0
1853-1904	6.4	4.6	0.5
1801-1853	3.7	2.6	0.5
1751-1801	3.6	2.7	0.6
1702-1751	4.1	3.2	0.5
1659-1702	5.4	4.1	0.5
1617-1659	10.5	3.7	0.5
1553-1617	16.0	10.6	0.5

II/III

	$\bar{X}$	SE	$\bar{X}f$
1904-1945	10.3	10.9	1.0
1850-1904	5.4	6.1	0.6
1800-1850	3.6	3.0	0.6
1752-1800	2.2	1.4	0.6
1705-1752	3.4	1.8	0.5
1650-1705	3.4	1.9	0.5
1604-1650	5.1	4.1	0.6
1559-1604	7.5	3.8	0.5
1502-1559	8.1	2.7	0.5
1459-1502	7.2	4.8	0.5
1399-1459	30.0	19.8	0.5

III/IV

	$\bar{X}$	SE	$\bar{X}f$
1904-1945	10.3	10.9	1.0
1855-1904	7.0	6.7	0.7
1805-1855	7.1	3.8	0.6
1751-1805	2.3	1.5	0.5
1712-1751	4.3	2.1	0.6
1654-1712	5.3	5.3	0.5
1598-1654	8.0	6.4	0.5
1557-1598	13.7	1.2	0.5
1492-1557	32.5	2.1	0.5
1459-1492	8.3	5.8	0.5

Appendix 3. continued.

IV/V

	$\bar{X}$	SE	$\bar{X}f$
1904-1945	10.3	10.9	0.9
1853-1904	6.4	6.5	0.6
1811-1853	5.3	3.2	0.7
1751-1811	3.5	2.8	0.6
1703-1751	3.7	2.3	0.5
1654-1703	3.5	2.6	0.5
1600-1654	6.8	5.3	0.6
1552-1600	5.3	3.8	0.6
1523-1552	29.0	--	0.5

V/VI

	$\bar{X}$	SE	$\bar{X}f$
1904-1945	13.7	11.9	1.0
1853-1904	5.7	4.7	0.7
1801-1853	4.0	2.9	0.6
1751-1801	3.8	2.8	0.6
1702-1751	3.3	3.2	0.5
1659-1702	3.3	3.7	0.5
1600-1659	5.9	4.7	0.5
1552-1600	5.3	4.9	0.6

VII/VIII

	$\bar{X}$	SE	$\bar{X}f$
1904-1945	13.7	11.9	1.0
1840-1904	8.1	9.4	0.5
1807-1840	3.7	2.2	0.5
1739-1807	6.0	5.8	0.6
1713-1739	7.7	4.5	0.7
1651-1713	20.7	9.5	0.5
1607-1651	8.8	3.2	0.5

Appendix 4. Summaries of mean fire intervals (years), standard error, and mean frequency of fire coincidence among composite groups (Xf) for foursome composites.

I/III/IV/V	X	SE	Xf
1904-1945	13.7	10.4	0.8
1853-1904	5.7	5.1	0.4
1802-1853	4.6	2.8	0.4
1751-1802	1.9	1.1	0.3
1701-1751	2.8	1.9	0.3
1654-1701	2.6	2.1	0.3
1600-1654	3.6	2.5	0.3
1552-1600	4.8	2.5	0.3
1514-1552	7.6	7.2	0.3
1459-1514	11.0	7.9	0.3

I/II/III/IV	X	SE	Xf
1904-1945	13.7	10.4	0.8
1850-1904	4.9	4.9	0.5
1800-1850	3.1	2.8	0.4
1751-1800	1.5	0.8	0.3
1701-1751	2.4	0.9	0.4
1650-1701	2.2	1.4	0.3
1602-1650	2.8	1.6	0.3
1557-1602	4.5	2.8	0.3
1502-1557	4.6	3.1	0.3
1459-1502	7.2	4.8	0.3
1399-1459	30.0	1.0	0.3

II/III/IV/V	X	SE	Xf
1904-1945	13.7	10.4	0.9
1850-1904	4.9	6.0	0.5
1800-1850	2.9	2.1	0.4
1751-1800	1.6	0.8	0.4
1703-1751	2.3	1.0	0.3
1650-1703	2.0	1.3	0.3
1600-1650	3.1	2.0	0.3
1552-1600	3.7	3.2	0.3
1502-1552	6.3	3.3	0.3
1459-1502	7.2	4.8	0.3
1399-1459	30.0	1.0	0.3

III/IV/V/VI	X	SE	Xf
1904-1945	13.7	10.4	0.8
1853-1904	3.4	2.4	0.4
1801-1853	3.5	2.4	0.4
1751-1801	1.7	1.0	0.3
1702-1751	2.1	1.4	0.3
1654-1702	2.1	1.4	0.3
1600-1654	3.6	3.2	0.3
1552-1600	4.0	3.3	0.3
1523-1552	29.0		0.3
1459-1523	12.8	11.3	0.3

IV/V/VI/VII	X	SE	Xf
1904-1945	13.7	10.4	0.8
1853-1904	3.6	3.7	0.4
1801-1853	2.7	1.4	0.3
1751-1801	1.9	1.3	0.4
1702-1751	2.0	1.2	0.3
1651-1702	2.3	1.4	0.3
1600-1651	3.2	2.0	0.3
1552-1600	4.0	3.3	0.3
1523-1552	29.0		0.3

IV/V/VI/VIII	X	SE	Xf
1904-1945	13.7	10.4	0.8
1853-1904	4.3	3.8	0.4
1801-1853	3.1	2.3	0.4
1751-1801	2.1	1.4	0.4
1702-1751	2.1	1.4	0.3
1654-1702	2.4	1.5	0.3
1600-1654	4.5	3.6	0.3
1552-1600	4.0	3.3	0.3
1523-1552	29.0		0.3

V/VI/VII/VIII	X	SE	Xf
1904-1945	20.5	2.1	1.0
1853-1904	4.6	4.4	0.3
1801-1853	2.5	1.4	0.3
1751-1801	2.8	2.0	0.3
1702-1751	2.6	1.8	0.3
1651-1702	3.2	3.1	0.3
1600-1651	3.6	2.5	0.3
1552-1600	5.3	4.9	0.3

Appendix 5. Fire dates by composite group.

COMPOSITE GROUPS

FIRE DATES AND INTERVALS

I		II		III		IV		V		VI		VII		VIII	
1990		1990		1990		1990		1990		1990		1990		1990	
1945	45	1945	45	1945	45	1945	45	1945	45	1945	45	1945	45	1945	45
1923	22	1923	22	1923	22	1923	22	1923	22	1923	22	1923	22	1923	22
		1906	17	1906	17	1906	17	1904	19	1904	19	1904	19	1904	19
		1904	2	1904	2	1904	2								
1886	37	1890	14	1890	14	1890	14	1890	14	1890	14	1875	29		
1857	29	1871	19	1871	19	1871	19	1863	27	1885	5	1866	9		
		1867	4	1863	8	1867	4	1855	8	1876	9				
		1859	8	1855	8	1859	8	1853	2	1865	11				
		1858	1			1857	2			1863	2				
		1857	1			1855	2			1857	6				
		1852	5							1856	1				
		1850	2							1853	3				
1844	13	1849	1	1848	7	1848	7	1848	5	1845	8	1834	32	1840	64
1837	7	1848	1	1824	24	1841	7	1837	11	1837	8	1817	17	1837	3
1824	13	1844	4	1805	19	1837	4	1828	9	1827	10	1815	2	1828	9
1802	22	1838	6			1824	13	1821	7	1824	3	1808	7	1820	8
		1837	1			1822	2	1811	10	1822	2	1807	1	1813	7
		1825	12			1811	11			1818	4				
		1824	1							1811	7				
		1822	2							1804	7				
		1818	4							1802	2				
		1815	3							1801	1				
		1811	4												
		1801	10												
		1800	1												
1792	10	1795	5	1781	24	1798	13	1798	13	1799	2	1793	14	1794	19
1788	4	1794	1	1773	8	1794	4	1787	11	1792	7	1788	5	1793	1
1774	14	1790	4	1770	3	1791	3	1768	19	1787	5	1787	1	1787	6
1770	4	1787	3	1766	4	1787	4			1786	1	1779	8	1776	11
1759	11	1786	1	1761	5	1783	4			1776	10	1760	19	1759	17
1752	7	1783	3	1760	1	1779	4			1771	5				
		1780	3	1757	3	1776	3			1768	3				
		1778	2	1753	4	1775	1			1767	1				
		1774	4			1771	4			1766	1				
		1773	1			1770	1			1759	7				
		1772	1			1768	2			1756	3				
		1771	1			1765	3			1751	5				
		1766	5			1759	6								
		1759	7			1755	4								
		1757	2			1754	1								

COMPOSITE GROUPS

I	II	III	IV	V	VI	VII	VIII
	1754 3		1752 2				
	1753 1		1751 1				
	1752 1						
1745 7	1748 4	1748 5	1748 3	1734 34	1749 2	1744 16	1742 17
1744 1	1744 4	1733 15	1744 4	1723 11	1742 7	1742 2	1724 18
1743 1	1741 3		1741 3	1706 17	1735 7	1733 9	
1733 10	1738 3		1736 5	1703 3	1733 2	1724 9	
1717 16	1736 2		1733 3		1732 1	1718 6	
1712 5	1731 5		1724 9		1731 1	1713 5	
1708 4	1728 3		1721 3		1728 3		
1701 7	1727 1		1715 6		1720 8		
	1726 1		1712 3		1708 12		
	1719 7				1705 3		
	1715 4				1702 3		
	1708 7						
	1705 3						
1688 13	1699 6	1692 41	1693 19	1694 9	1698 4	1685 28	
1672 16	1693 6	1671 21	1689 4	1690 4	1693 5	1661 24	
1671 1	1684 9	1657 14	1681 8	1687 3	1691 2	1651 10	
	1679 5		1672 9	1680 7	1688 3		
	1678 1		1670 2	1675 5	1683 5		
	1674 4		1667 3	1674 1	1677 6		
	1673 1		1661 6		1674 3		
	1666 7		1654 7		1659 15		
	1661 5						
	1656 5						
	1652 4						
1637 34	1650 2	1646 11	1644 10	1648 26	1647 12	1638 13	
1621 16	1641 9	1641 5	1624 20	1627 21	1634 13	1627 11	
1613 8	1640 1	1626 15	1616 8	1621 6	1629 5	1622 5	
1606 7	1638 2			1616 5	1617 12	1615 7	
1602 4	1632 6			1603 13		1607 8	
	1627 5			1600 3			
	1612 15						
	1604 8						
1561 41	1594 10		1598 18	1593 7	1587 30		
	1591 3		1585 13	1588 5	1582 5		
	1587 4		1572 13	1582 6	1570 12		
	1578 9		1557 15	1578 4	1553 17		
	1572 6			1572 6			
	1559 13			1552 20			

Figure 6b. Enlargement of scar sequences on Fish Gulch sample shown at far right in Figure 6a. Note small sizes of individual fire scar callus tissues.

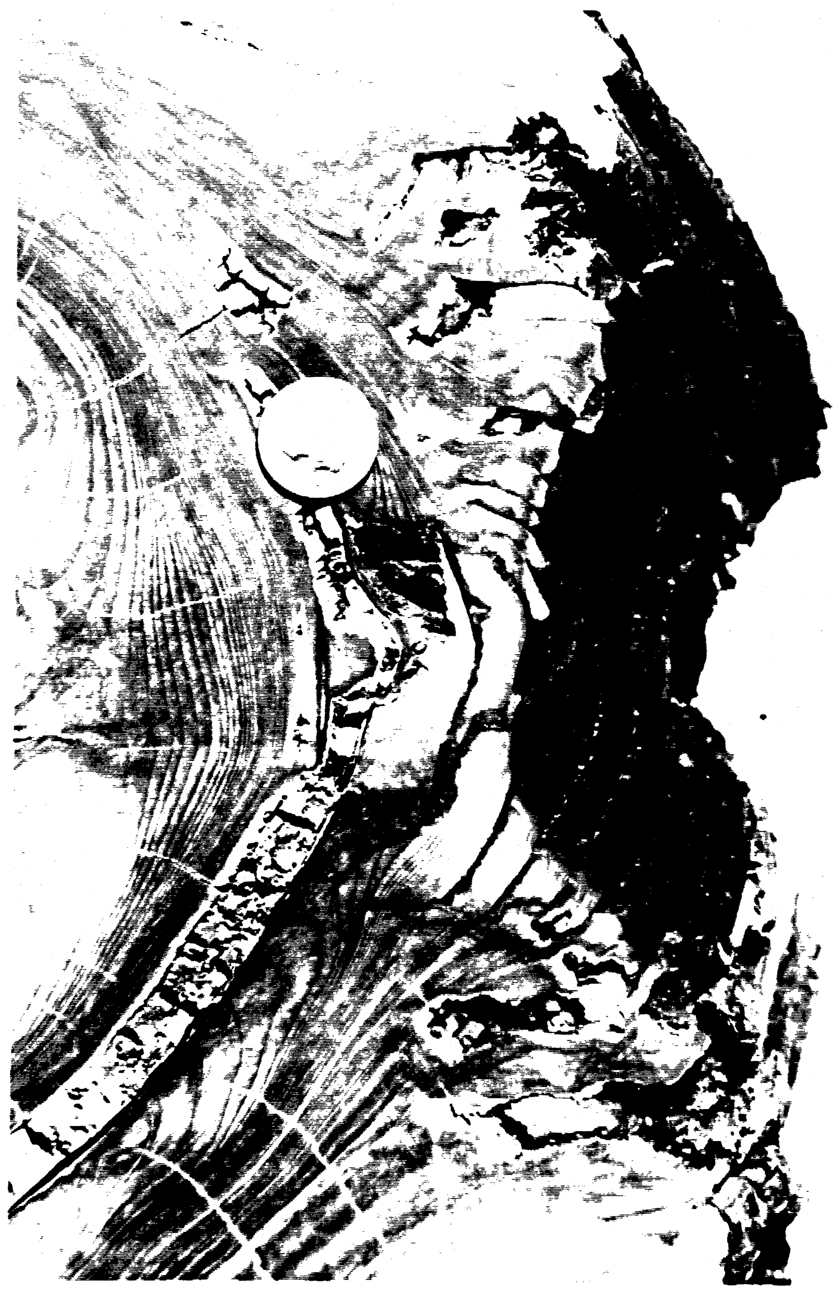


Figure 6c. Example partial cross-section from a redwood stump on Bolinas Ridge showing fire scar sequence.

Comments on Fire History Report

Any apparent conflicts between the fire history findings of the redwood fire scar analysis and those of the documented fire occurrences do not necessarily suggest actual incongruities of temporal trends in either fire sizes or numbers. Contrasts between the results of the studies more likely reflect (1) differences in methods used, (2) the vegetation types in which fires burned, and (3) the time periods covered by the analyses.

(1) Fire history information gained from fire scar analysis tends to be less complete than from documentation of fires by human witnesses. In particular, scar evidence from small fires is less likely to be discovered during reconaissance or sampling than evidence from larger fires; small fires scar fewer trees and thus are more likely to be overlooked during sampling as well as to be destroyed by later fires. Fire scarring is also less likely during smaller fires because fuel moisture and weather conditions that maintained a fire small before it was supressed are less conducive to fire scarring. Also, fire scars only reveal the presence or absence of a fire at a particular point in time (usually to the year but sometimes within the growing season of a year); spatial extent of fires must be reconstructed from point data. Witnesses can document the spatial extent of fires which may burn for many months over a vast area; witnesses can also report on characteristics of fires.

(2) The results of the redwood fire history study suggest that large-scale fires in redwood forest vegetation have dominated during the past 100 years and small fires have been less numerous. This must be interpreted knowing 1. that smaller fires were not detected as consistently as larger fires (above), 2. that fire extent must be reconstructed from point data rather than supplied as fire records (above), 3. that redwood understory fuels are less flammable under given conditions than grass fuels and thus less likely to propagate a potential ignition into a detected fire, and 4. that ignition sources are presently less prevalent in redwood forests (without the logging or firewood cutting that occurred in the mid 19th century) compared to more populated and heavily used grass and shrubland areas near paved roads used by recreationists and arsonists. The fire scar analysis was restricted to areas where multiple fire scar evidence is available from pre-settlement periods (i.e. areas forested by redwood). Fires documented by fire departments or fire suppression personnel can and have burned in any vegetation and fuel type; evidence of more than one fire in grass, shrub, and many forest vegetation types is not preserved for later analysis. In fact, evidence of a single fire may not be detectable for more than a few months after a grass burn.

(3) In addition to the previously mentioned problems with comparing the two types of data, the contrast between the suggested increase in fire numbers and decrease in sizes (documented fire history) and decrease in fire numbers and increase in sizes (fire scar analysis) is likely an artifact of juxtaposed historical time periods. Data from the fire scar analysis extended from approximately the 1600's to 1945 whereas the earliest documented fire history data began during the mid- to late-1800's and ended in the 1980's. Both types of data are less accurate and less complete for older fires. Documented fire history from the suppression period (post 1930), for which most comparisons are drawn with the pre-suppression period, coincides with a period when only one fire (1945) was detected by the scar analysis. These data types and their respective time scales and fire occurrence resolutions are not really comparable for these time periods for this reason alone. In addition, fire data change in accuracy and completeness with time; fire scar data become less complete prior to the 1600's because evidence is not preserved, and written fire occurrence records have become more accurate and complete since the advent of active fire suppression due to increased attention to fires, increased detection capabilities, and improved record keeping standards.